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Compilation of Water-Resources Data and Hydrogeologic Setting for Four Research Stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina, 2000–2004

Open-File Report 2006–1168

U.S. Department of the Interior
U.S. Geological Survey

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2006	**N/A**	**-**

4. TITLE AND SUBTITLE
Compilation of Water-Resources Data and Hydrogeologic Setting for Four Research Stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina, 2000-2004

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of the Interior 1849 C Street, NW Washington, DC 20240

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

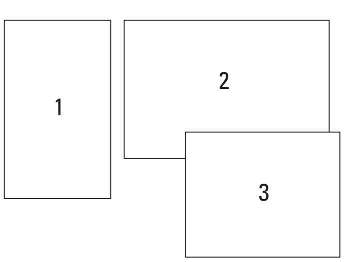
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**116**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Cover.



1 – North Carolina Department of Environment and Natural Resources, Division of Water Quality, drillers installing a monitoring well *(photograph by Donald J. Geddes, Jr., USGS)*

2 – Well cluster MW–S1 at the Upper Piedmont research station *(photograph by Donald J. Geddes, Jr., USGS)*

3 – Data-collection platform at well cluster MW–2 at the Bent Creek research station *(photograph by Brad A. Huffman, USGS)*

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U.S. Geological Survey, Reston, Virginia: 2006

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Suggested citation:
Huffman, B.A., Pfeifle, C.A., Chapman, M.J., Bolich, R.E., Campbell, T.R., Geddes, D.J., Jr., and Pippin, C.G., 2006, Compilation of water-resources data and hydrogeologic setting for four research stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina, 2000–2004: U.S. Geological Survey Open-File Report 2006–1168, 102 p., available online at *http://pubs.water.usgs.gov/ofr2006–1168*

Contents

Figures

Tables

Conversion Factors, Vertical Datum, Temperature, and Definitions

Multiply	By	To Obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	Pressure	
pound per square inch (lb/in^2)	6.895	Kilopascal (kPa)

Vertical coordinates: Vertical coordinates in this report are referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinates: Horizontal coordinates (latitude and longitude) in this report are referenced to the North American Datum of 1983 (NAD 83).

Temperature: In this report, water temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = (1.8 \times °C) + 32$$

Water-quality measurements:

µS/cm	microsiemens per centimeter at 25 °C
µg/L	microgram per liter
mg/L	milligram per liter

Acronyms and abbreviations:

BAT3	Bedrock-Aquifer Transportable Testing Tool
BCRS	Bent Creek research station
DCP	data-collection platform
DO	dissolved oxygen
DWQ	Division of Water Quality
GNF	felsic gneiss hydrogeologic unit
GNM	mafic gneiss hydrogeologic unit
GP	geoprobe
GWSI	Ground Water Site Inventory
IQR	interquartile range
LPRS	Langtree Peninsula research station
LWRRS	Lake Wheeler Road research station
MII	intermediate metaigneous hydrogeologic unit
MP	measuring point
MW	monitoring well
NCDENR	North Carolina Department of Environment and Natural Resources
NCGS	North Carolina Geological Survey
NCSU	North Carolina State University
NWIS	National Water Information System
OTV	optical televiewer
PVC	polyvinyl chloride
PW	pumping well
PZ	piezometer
PMREP	Piedmont and Mountains Resource Evaluation Program
QTZ	quartzite hydrogeologic unit
SC	specific conductance
SOP	standard operating procedure
SWETC	Soil and Water Environmental Technology Center
UPRS	Upper Piedmont research station
USGS	U.S. Geological Survey
WL	water level or augered well

Compilation of Water-Resources Data and Hydrogeologic Setting for Four Research Stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina, 2000–2004

By Brad A. Huffman[1], Cassandra A. Pfeifle[1], Melinda J. Chapman[1], Richard E. Bolich[2], Ted R. Campbell[2], Donald J. Geddes, Jr.[2], and Charles G. Pippin[2]

Abstract

Water-resources data were collected to describe the hydrologic conditions at four research stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina. Data collected by the U.S. Geological Survey and the North Carolina Department of Environment and Natural Resources, Division of Water Quality, from September 2000 through September 2004 are presented in this report. The locations and periods of data collection are as follows: the Lake Wheeler Road research station (Raleigh) from April 2001 to September 2004, the Langtree Peninsula research station (Mooresville) from September 2000 to September 2004, the Upper Piedmont research station (Reidsville) from March 2002 to September 2004, and the Bent Creek research station (Asheville) from July 2002 to September 2004.

Data presented in this report include well-construction characteristics for 110 wells, periodic ground-water-level measurements for 96 wells, borehole geophysical logs for 23 wells, hourly ground-water-level measurements for 12 wells, continuous-stage measurements for 2 streams, continuous water-quality measurements for 8 wells and 2 streams, periodic water-quality samples for 57 wells and 6 stream sites, slug-test results for 38 wells, and shallow ground-water-flow maps. In addition, the geology and hydrogeology at each site are summarized.

Introduction

In 1999, the U.S. Geological Survey (USGS) and the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality (DWQ), began a multiyear cooperative study to measure ambient ground-water quality and describe the ground-water-flow systems at selected research stations in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina (Daniel and Dahlen, 2002). The study is supported by the Piedmont and Mountains Resource Evaluation Program (PMREP), which was created by the North Carolina Legislature to ensure the long-term availability, sustainability, and quality of ground water in the State. The study was designed to be a 10-year, intensive field investigation at research stations established in representative hydrogeologic settings across the State. To date (2006), eight research stations have been selected for study in the Piedmont and Blue Ridge Physiographic Provinces (fig. 1), and wells have been installed at six of these research stations. Data from research stations in Raleigh, Mooresville, Reidsville, and Asheville are included in this report. These data are providing information to refine the historical conceptual ground-water-flow models for the Piedmont and Blue Ridge Physiographic Provinces in North Carolina and the Southeastern United States.

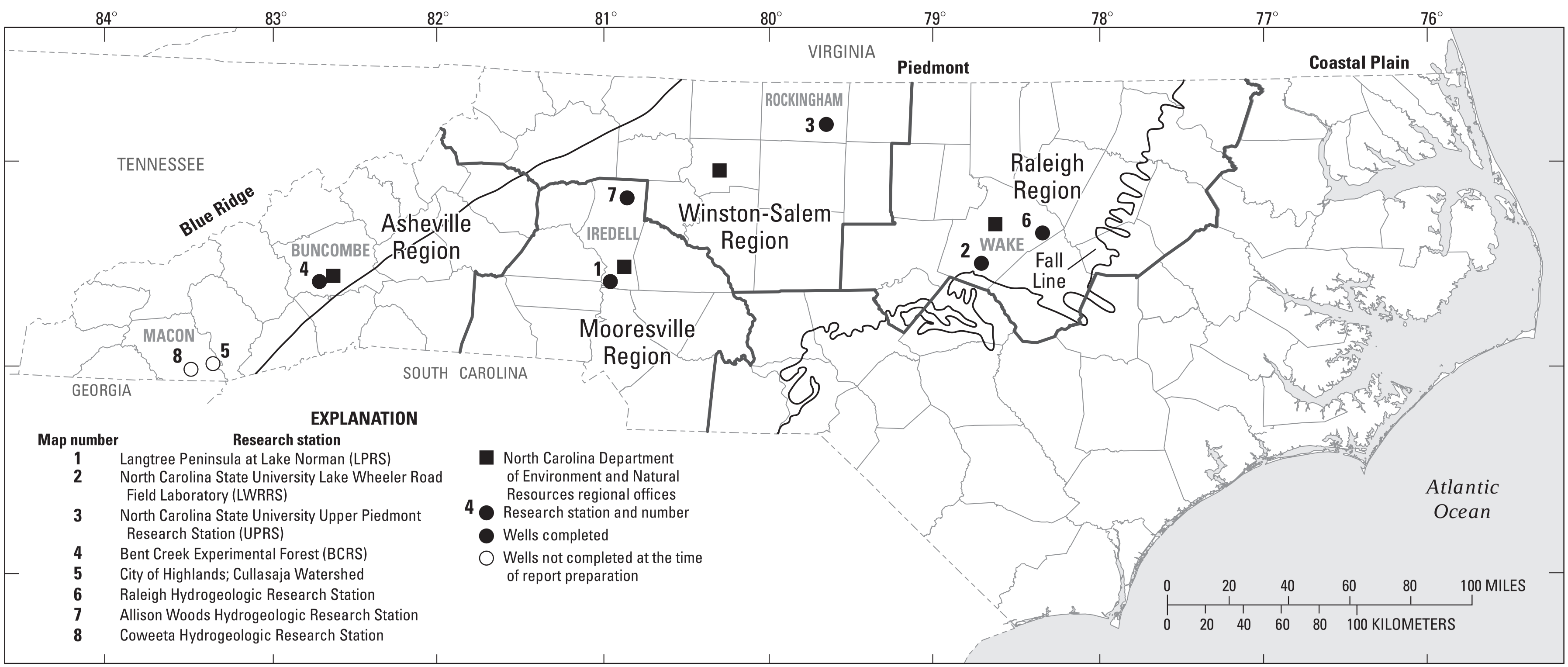
One of the primary objectives of the PMREP in installing research stations in representative hydrogeologic settings is to evaluate the spatial and temporal variation of ambient ground-water levels and ground-water-quality data across the Piedmont and Blue Ridge Physiographic Provinces. The research stations generally consist of transects of monitoring-well clusters located parallel to an assumed flow path within a conceptual "slope-aquifer" system, described by LeGrand and Nelson (2004), from recharge to discharge areas. Well clusters are designed to monitor separate zones in the ground-water system, including the shallow regolith, transition zone, and deep bedrock (Chapman and others, 2005).

Purpose and Scope

The purpose of this report is to summarize data collected from September 2000 through September 2004 at four of

[1]U.S. Geological Survey, North Carolina Water Science Center.

[2]North Carolina Department of Environment and Natural Resources, Division of Water Quality, Aquifer Protection Section.



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 1. Research stations selected for investigations as part of the cooperative U.S. Geological Survey-North Carolina Division of Water Quality Piedmont-Mountains Ground-Water Study in North Carolina.

the PMREP research stations. Data are presented for (1) Lake Wheeler Road research station in Raleigh (LWRRS), (2) Langtree Peninsula research station in Mooresville (LPRS), (3) Upper Piedmont research station in Reidsville (UPRS), and (4) Bent Creek research station in Asheville (BCRS). Descriptions of the regional surficial geology, research station design, well characteristics, borehole geophysical data, and ground-water-level data are included in separate sections of this report for each research station.

Description of the Study Areas

The Piedmont and Blue Ridge Physiographic Provinces in North Carolina encompass about 30,544 square miles (mi^2) in 54 counties. In 2000, the population of this area was about 6.11 million, and the total ground-water use was estimated to be about 244 million gallons per day (U.S. Geological Survey, 2005a). Ground water is the primary source of drinking water in most rural and some suburban areas of the State, whereas surface water is the primary drinking-water source in the metropolitan areas (Daniel and Dahlen, 2002). Most of the population lives in or near the metropolitan areas of Raleigh/Durham/Chapel Hill, Greensboro/Winston-Salem, and Charlotte, all of which are located in the Piedmont Physiographic Province (Chapman and others, 2005).

The geology of most of the Piedmont and Blue Ridge Provinces is complex. Rocks have undergone several episodes of intense metamorphism, folding, faulting, and igneous intrusion. In North Carolina, the regional sequences of rocks are grouped into belts (North Carolina Geological Survey, 1985; fig. 2). Although the rocks in these belts generally are similar with respect to lithology, more variation and complexity can be observed on a local scale. Daniel and Dahlen (2002) provided an overview of the major hydrogeologic units of the Piedmont and Blue Ridge Provinces in reference to the geologic belts of the State. The four research stations discussed in this report are in the Raleigh litho-tectonic belt (LWRRS), the Charlotte litho-tectonic belt (LPRS), the Milton litho-tectonic belt (UPRS), and the Blue Ridge litho-tectonic belt (BCRS; fig. 2).

The humid, subtropical climate in the study areas is typical for the Southeastern United States. The average annual precipitation is 40 to 50 inches, which is distributed fairly evenly throughout the year. Hydrologic conditions in water years[3] 2000–2002 were affected by drought conditions, water year 2003 was considered above normal, and water year 2004 was considered normal (Weaver, 2005).

[3]Water year is the period from October 1 through September 30 and is identified by the year in which the period ends. The 2004 water year, for example, was the period October 1, 2003, through September 30, 2004.

Acknowledgments

The authors thank members of the North Carolina Department of Environment and Natural Resources and the USGS Resource Evaluation Program who continue to contribute to data collection and analysis for this project. PMREP members include Landon Davidson of the Asheville Regional Office, Aquifer Protection Section, and M. Carl Bailey and Walter T. Haven of the Raleigh DWQ Central Office Planning Branch. In addition, the authors thank the DWQ drillers for their support of data collection in the field, and the following individuals for their support of this project and assistance in facilitating field-site access: Sterling Martin, Manager of the Davidson College Lake Campus; Henry McNab, U.S. Forest Service, Bent Creek Experimental Forest; Ken Snyder, Manager of the North Carolina State University Lake Wheeler Road Field Laboratory; Joe French, Ph.D., Superintendent of the Upper Piedmont Research Station; and Jeff North, Director of the Betsy-Jeff Penn 4–H Educational Center.

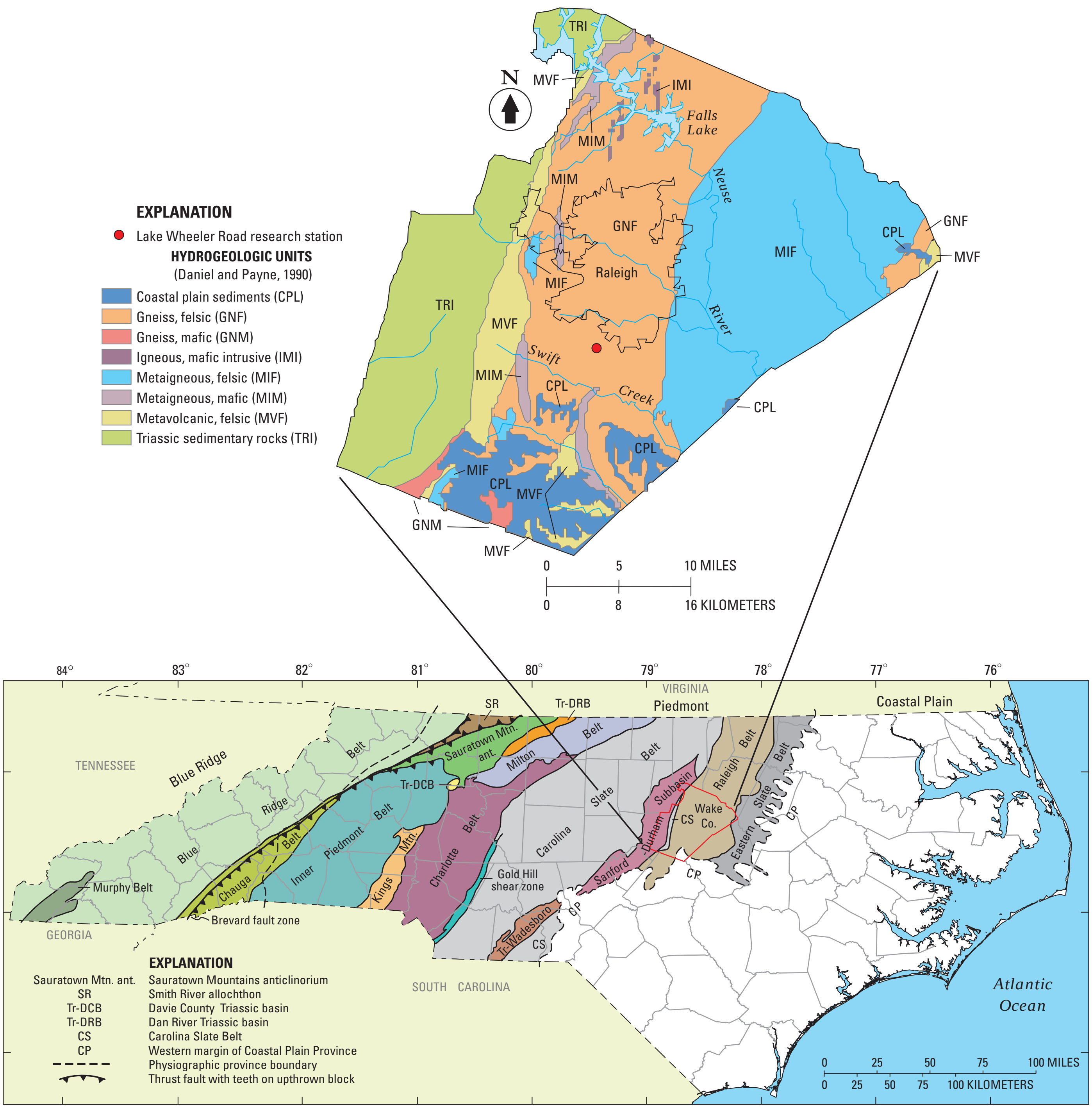
Methods of Data Collection

Activities described in this report support the investigative work of the overall regional PMREP. Data-collection methods used at each research station are summarized here and in the standard operating procedures (SOP) for the PMREP (North Carolina Department of Environment and Natural Resources, 2002).

Well Construction

The research stations generally consist of a topographic transect of monitoring-well clusters. Each transect includes well clusters located within a conceptual "slope-aquifer" system, described by LeGrand and Nelson (2004), from recharge (higher elevations, such as hilltops) to discharge areas (lower elevations, such as stream valleys). Well clusters are designed to monitor three separate zones in the ground-water system—the regolith, the transition zone between regolith and bedrock, and the deeper bedrock. The regolith zone includes soil residuum, alluvium, colluvium, and saprolite. The transition zone consists of partially weathered rock and open fractures near the top of bedrock. At some stations, shallow regolith wells were not installed because of greater depth to the water table. Piezometers were installed at some research stations to better describe horizontal and vertical ground-water flow and to conduct aquifer tests. To date (2006), 160 wells and piezometers have been installed at six research stations (fig. 1). Data from four research stations (110 wells and piezometers) are summarized in this report.

Well-construction methods are described in Chapman and others (2005). Well-construction data are given in tables and in the specific site-description sections of this report.



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U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 2. Locations of Lake Wheeler Road research station, hydrogeologic units in Wake County, and geologic belts delineated in the Piedmont Physiographic Province of North Carolina (modified from North Carolina Geological Survey, 1985; Daniel and Payne, 1990).

Well and Surface-Water Station Numbering System

Wells and surface-water stations installed by the USGS are given unique identification numbers based on geographic location. A latitude-longitude system is used for wells and a downstream-order system is used for surface-water stations. The latitude and longitude of each well cluster and the surface-water station at the LWRRS were determined by using a differential global positioning system receiver and are considered accurate to within a few feet (Chapman and others, 2005).

Wells were assigned a 15-digit site number based on the latitude and longitude of each well or, in the case of this study, well cluster. The latitude and longitude constitute the first 13 digits, respectively, and are followed by a 2-digit sequence number used to distinguish between wells at the same location. Each well in a cluster has the same site-identification number except for the last 2 digits. Typically, the assigned sequence numbers begin with 01 for the shallowest well and progress with well depth. Thus, the deeper the well, the higher the sequence number (Chapman and others, 2005).

The wells in this study were also assigned a local identifier, which consists of a two-letter county code followed by a three-digit sequence number. For example, wells in Wake County are identified by the prefix “WK” followed by three numbers assigned sequentially. The station name includes the site identifier (Lake Wheeler Road research station), well descriptor, and number. The well descriptors used in this study are as follows: MW for monitoring well, PW for pumping well, PZ for piezometer, GP for geoprobe, and WL for water level. For the purpose of this study, GP and WL are the same as piezometers or aquifer-test wells. Following the well descriptor is a cluster number and a letter, which indicates the aquifer section or zone that is being monitored: S for shallow zone (regolith), I or T for transition zone, and D for deeper zone (bedrock). For example, well MW–1S is a monitoring well in cluster 1 and is completed in the shallow regolith zone (Chapman and others, 2005).

The downstream order number or station number assigned to a surface-water station is based on the location of the station in the downstream direction along the main stem of the stream. The first two digits of the 8- to 10-digit station number identify the hydrologic unit (U.S. Geological Survey, 1974, 1975) used by the USGS to designate the major drainage system. The next 6 digits indicate the downstream order within the major drainage system. An additional 2 digits are added at the end of the station number in areas of high station density (Chapman and others, 2005).

Borehole Geophysical Logging

Borehole geophysical logs were collected in three phases. The first phase of geophysical logging included the collection of traditional logs—caliper, natural gamma, electrical (resistance, short-normal, long-normal, and lateral resistivity), and fluid (temperature, fluid resistivity) logs. The second phase of logging included the measurement of vertical flow near fracture zones using a heat-pulse flowmeter, with a measurement range of about 0.01 to 1.5 gallons per minute (gal/min; U.S. Geological Survey, 2005b). Heat-pulse flowmeter logging was conducted under ambient and(or) stressed conditions. Stressed conditions were created by pumping the well at a constant rate depending on well yield or by drawing the water level down and logging during recovery. The third phase of logging included the collection of a borehole image using an oriented digital camera, the optical televiewer (OTV). The OTV data enable the identification of lithology type (felsic or mafic), rock-foliation orientation, and fracture orientation. The orientation data are displayed in tadpole plots, where dip angle is plotted as a circle and azimuth direction is plotted as a line segment. The OTV data were corrected for magnetic declination and borehole deviation (azimuth and inclination angle). All geophysical logs collected and reported here are referenced to feet below land surface (Chapman and others, 2005).

Continuous Monitoring

Continuous monitoring of water levels, stream stage, and water quality were conducted at the four research stations included in this report. The periods of record for the data collection are described in the individual research station sections of the report. Data were collected at a specified interval (hourly or 15-minute) and transmitted by satellite every 4 hours to a USGS database for processing and then made accessible in the USGS National Water Information System (NWIS) database from the USGS North Carolina Water Science Center Web page *http://waterdata.usgs.gov/nc/nwis/*. Ground-water levels were measured hourly at all sites by using a submersible pressure transducer or a float and tape system with an incremental encoder. Stream stage was measured every 15 minutes by using a gas-purge system and nonsubmersible pressure transducer. Water-quality samples were collected hourly in the wells and every 15 minutes at the surface-water sites by using multiparameter water-quality probes. Ground-water and surface-water data collected at the study sites during water years 2002–04 are published in USGS annual data reports (Howe and others, 2003, 2004, and 2005).

A network of continuous ground-water-level recording stations was established in 12 wells at 3 research stations. Both the pressure transducers and floats were checked periodically against a steel or electric tape to ensure accurate readings. Water-level data are stored in NWIS relative to feet below land surface. In this report, ground-water-level data are presented in feet above the North American Vertical Datum of 1988 (NAVD 88).

Continuous surface-water stage recorders were established on a stream at two research stations—LWRRS and UPRS. Fifteen-minute stage (water-level) data were obtained

using a gas-purge system. The system is equipped with a built-in compressor and nonsubmersible pressure transducer. An orifice mounted in the stream channel is connected by an air line to the gas-purge system, which is located in an instrument shelter on the bank. Every 15 minutes, the compressor purges any air that may be in the line, and the pressure transducer records a pressure reading. The reading then can be referenced to stage height by using the actual water level on an outside staff gage. Both the orifice and the outside staff gage are anchored in the stream with a 2-inch protective steel pipe. In this report, stage data are presented in feet above NAVD 88.

A network of continuous ground-water-quality stations was established in eight wells and at two surface-water stations. Water-quality data were collected hourly in wells and at 15-minute intervals at the surface-water sites by using multiparameter water-quality probes. The following water-quality properties were measured: water temperature, dissolved oxygen (DO), pH, and specific conductance (SC). The water-quality probes were inspected and cleaned at least once a month according to USGS guidelines (Wagner and others, 2006).

All of the water-quality probes and pressure transducers are connected to a data-collection platform (DCP) where the data are recorded and transmitted. Separate DCPs were used for the wells and for the streams. Each DCP was powered by a 12-volt battery and equipped with a solar panel to recharge the battery. Each DCP is housed in a sealed aluminum shelter and grounded with a copper wire for surge and lightning protection. Wiring is buried 6–12 inches below ground and is protected by flexible steel tubing.

Periodic Water-Level Measurements

Periodic ground-water levels were measured monthly or bimonthly at all of the wells at each research station to identify seasonal ground-water trends in each of the three zones (regolith, transition zone, and fractured bedrock) and to qualitatively describe vertical hydraulic gradients between wells in each cluster. Measurements were made using either a steel tape or an electric water-level tape from a specified measuring point (MP) on top of the well casing. The MP and land surface at each well were surveyed, and the altitudes were tied in to a local surveyor's concrete monument or an established benchmark in order to determine the MP and water-level altitude above NAVD 88. Typically, water levels are recorded in feet below land surface. Water-level data were entered into the USGS Ground Water Site Inventory (GWSI) database and are available online at *http://nwis.waterdata.usgs.gov/nc/nwis/gwlevels*, and in USGS annual data reports (Howe and others, 2003, 2004, and 2005). In this report, periodic ground-water levels are presented in feet above NAVD 88.

Slug Tests

Rising and falling slug tests were performed on 38 of the monitoring wells installed as part of the PMREP to assess the hydraulic conductivity at the well-site locations. Either solid polyvinyl chloride (PVC) slugs or PVC bailers were used to displace water in the wells. The solid slug or bailer was rinsed with distilled water before use in each well. A submersible pressure transducer with an integrated electronic data logger was used to measure water-level fluctuations during each test. A laptop computer was used to monitor and download the transducer readings. Water-level data recorded on the transducer data logger were verified with manual water-level measurements.

When the solid slug was used, both falling (slug-in) and rising (slug-out) head data were analyzed. When a bailer was used, only rising (slug-out) head data were analyzed. The falling head slug test measured the rate at which water levels returned to static conditions after the introduction of the solid PVC slug. The rising head slug test measured the recovery of water levels to static conditions after the slug was removed. Efforts were made to avoid splashing effects during the introduction of the slug below the water level. The tests were terminated after water levels recovered to within 95 percent of the pre-test, static level.

The slug-test data for this investigation were analyzed using the Bouwer and Rice (1976) method. The Bouwer and Rice method accounts for partial penetration effects and changing aquifer thickness (water-table conditions). A basic assumption of this analytical method is that the aquifer is representative of a porous media and is considered isotropic, having no directional variation in hydraulic properties within the zone being tested. Additional assumptions are that the effects of elastic storage can be neglected and that the position of the water table does not change during the slug test (Butler, 1998). Spreadsheets developed by Halford and Kuniansky (2002) were used for analytical interpretations of slug-test data (Chapman and others, 2005).

Water-Quality Sampling and Laboratory Analysis

Water-quality samples were collected from each monitoring well and nearby stream or lake at each research station by following standard USGS protocols (Wilde and others, 1999). Sampling methods included the use of submersible pumps and peristaltic pumps. Water-quality properties (pH, SC, DO, and temperature) were monitored continuously using a multiparameter water-quality instrument and flowthrough chamber as ground water was removed from the well. Prior to sample collection, at least three well volumes of ground water were removed from the 4-inch diameter, shallow, screened wells tapping the regolith and transition zone. For the deeper, 6-inch diameter, open-borehole bedrock wells, extracting three volumes of ground water prior to

sample collection was impractical when using the submersible sampling pumps. For these wells, a minimum of one volume of casing water was removed, and water-quality properties were allowed to stabilize prior to sample collection. Pumps were placed near the more dominant fracture zones (Chapman and others, 2005). Analytical results of the water-quality sampling are published in USGS annual data reports (Howe and others, 2003, 2004, and 2005).

A multifunction Bedrock-Aquifer Transportable Testing Tool (BAT3; Shapiro, 2001) was used to collect water-quality samples at LWRRS and UPRS. The BAT3 allows discrete intervals of a borehole to be isolated hydraulically for geochemical sampling by using two inflatable packers that seal against the borehole wall; the spacing between the two packers defines the test interval in the borehole (Shapiro, 2001). The equipment is configured with a submersible pump located between the packers to withdraw water from the test interval in order to collect water-quality samples. The length of the test interval and the depth at which water-quality samples are collected were determined on the basis of the location of fractures intersecting the borehole, as identified by using borehole geophysical logs. A complete discussion of the downhole components of the BAT3 and its operation is given in Shapiro (2001).

Water samples were analyzed by the USGS National Water Quality Laboratory in Denver, Colorado. The water-quality constituents analyzed include major ions, nutrients, metals, radon 222 (gas), and radiochemicals. Of these, only samples for major ions and nutrients were collected during each sampling event. Water samples for all other constituents were collected intermittently (Chapman and others, 2005).

Statistical Analysis of Water-Quality Data

Box plots, Piper diagrams, and Stiff diagrams were used to analyze the statistical and geochemical variability in the periodic water-quality data. Prior to the statistical analysis, a quality-assurance check was conducted on the water-quality data. A mass balance with less than 10-percent difference for the major cations and anions was considered acceptable, and only these data were used in the statistical analysis.

Box plots statistically categorize data, identify outliers, and can be an effective means of comparing values between data sets. The box encompasses the interval between the first and third quartiles, also known as the interquartile range. The median is represented by a horizontal line within the rectangular box. The minimum and maximum values of the data set are represented by a whisker attached to a vertical line drawn from the first and third quartiles, respectively, to those values. A data point is a suspect outlier if it lies between 1.5 and 3 times the interquartile range, and highly suspect outliers are data points that occur at more than 3 times the interquartile range (Sincich, 1993).

Water-quality data also can be compared using Piper trilinear diagrams (Piper, 1953) and Stiff diagrams (Stiff, 1951). In a Piper diagram, the percentages of cations are plotted in the left trilinear diagram, and the percentages of anions are plotted in the right trilinear diagram. The diamond-shaped middle diagram plots the cations and anions together. Stiff diagrams show the dominant milliequivalent-per-liter concentrations of anions and cations present in the collected samples. In this report, water-quality data are presented by surface water and by ground-water-system zone (regolith, transition zone, and bedrock).

Lake Wheeler Road Research Station

Site Description and Geology

The Lake Wheeler Road research station (LWRRS) in Wake County was the first hydrogeologic research station installed as part of the North Carolina PMREP study (fig. 2). The LWRRS is located at the North Carolina State University (NCSU) Lake Wheeler Road Field Laboratory, which also includes the Soil and Water Environmental Technology Center (SWETC). The study area encompasses approximately 7 acres, about 5 miles southwest of the center of Raleigh, NC.

The LWRRS lies in the Raleigh litho-tectonic belt in the eastern Piedmont Physiographic Province and is underlain by a metamorphosed felsic gneiss that is part of the Raleigh Formation (Parker, 1979; Heller, 1996; fig. 2). Felsic gneiss represents about 20 to 30 percent of the geologic setting of the Piedmont and Blue Ridge Provinces in North Carolina. The LWRRS was selected for study (Daniel and Dahlen, 2002) to evaluate the effects of felsic gneiss rock type and steeply dipping foliation on ground-water quality, the thickness and composition of the regolith, the thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures (Chapman and others, 2005). Work conducted from April 2001 to September 2004 at the LWRRS included the collection and logging of three soil and rock core samples totaling 453 feet (ft) and the installation of 10 observation wells grouped into three clusters aligned along a transect. Three piezometers and one designated bedrock pumping well were installed for water-level and aquifer-test monitoring. Additional work included the installation of a real-time data-collection platform for continuous monitoring of water levels and water quality in one of the well clusters, monthly collection of water levels, semiannual sampling of wells, a 55-hour aquifer test in a bedrock well, slug tests, and borehole geophysical logging.

Well Construction

Three ground-water monitoring-well clusters were constructed, along with an aquifer-test well and three regolith piezometers (fig. 3). Well-cluster locations were

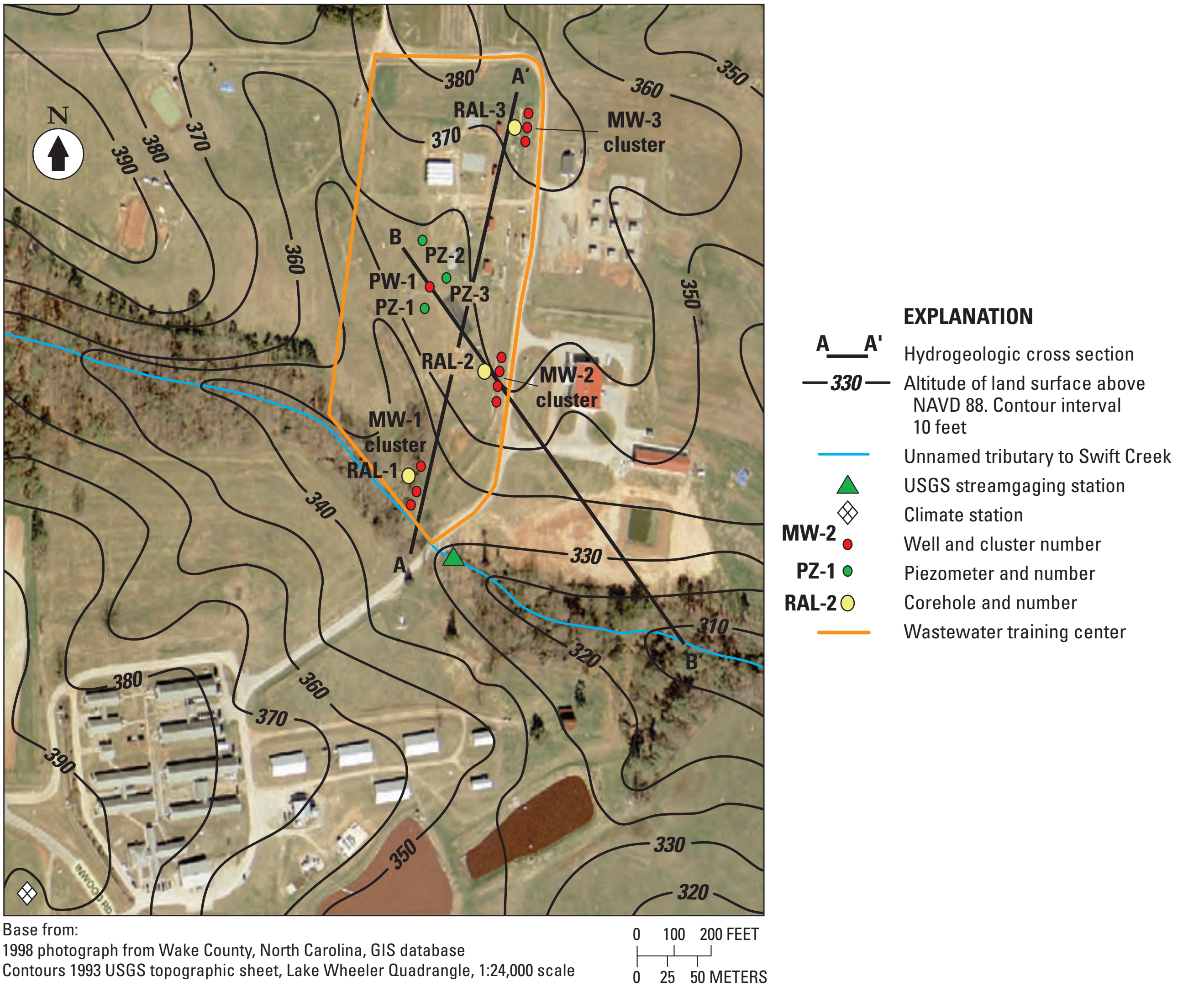

Figure 3. Aerial photograph overlaid with topographic features showing locations of well clusters, streamgaging station, climate station, and lines of section at the Lake Wheeler Road research station in Wake County, North Carolina.

selected to obtain water-quality and water-level data along a topographic transect in areas of recharge and discharge based on conceptual models developed for the slope-aquifer system (LeGrand and Nelson, 2004). During this study, 14 wells and piezometers were installed at the LWRRS (table 1). Criteria for well locations included topographic setting, accessibility, and site boundaries. Cross-section A–A', generally constructed along the well transect from well cluster MW–1 to well cluster MW–3, is depicted in figure 4A. Cross-section B–B', constructed along the well transect from PW–1 to an unnamed tributary, is depicted in figure 4B. Well cluster MW–3 is located in a conceptual recharge area, and well cluster MW–1 is located in a discharge area near the unnamed tributary. Four other wells (PW–1, PZ–1, PZ–2, and PZ–3) were installed to provide additional data during aquifer tests and for hydrogeologic site characterization.

Each well cluster at the LWRRS consists of at least three wells—a shallow well to monitor ground-water conditions in the regolith, a transition-zone well to monitor ground-water conditions in partially weathered rock and open fractures near the top of bedrock, and a deeper well to monitor ground water in the fractured bedrock (fig. 4). Well-construction information is provided in table 1. Well cluster MW–2 contains a fourth well (MW–2T) completed in the transition zone. Also, an inflatable packer was installed in well MW–1D on July 16, 2002, to monitor open fractures in the transition zone (MW–1DUZ) from 47 to 70 ft below land surface and in the bedrock lower fracture zone (MW–1DLZ) from 70 to 300 ft below land surface.

Table 1. Construction characteristics of monitoring wells and the surface-water site at the Lake Wheeler Road research station, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; MW, monitoring well; S, shallow; PVC, polyvinyl chloride casing; R, regolith; I or T, transition zone; D, deep; B, bedrock; PW, designated pumping well; Galv. Steel, galvanized steel; PZ, piezometer; na, not applicable; SW, surface water]

Site identification	Station name (fig. 4)	Construction date	Land-surface altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
						from	to		
354356078403501	MW–1S	5/24/2001	334.38	PVC	4.0	5	20	0.01 slotted PVC	R
354356078403502	MW–1I	5/29/2001	335.36	PVC	4.0	31.5	41.5	0.01 slotted PVC	I
354356078403503	MW–1D	6/5/2001	338.62	PVC	6.0	47	302	Open hole	B
354356078403504	MW–1DUZ[a]	7/16/2002	338.62	PVC	6.0	47	75[b]	Open hole	T
354356078403505	MW–1DLZ[a]	7/16/2002	338.62	PVC	6.0	75[b]	302	Open hole	B
354359078403101	MW–2S	5/9/2001	362.00	PVC	4.0	20	40	0.01 slotted PVC	R
354359078403102	MW–2I	5/9/2001	361.19	PVC	4.0	40	50	0.01 slotted PVC	I
354359078403103	MW–2T	5/9/2001	360.44	PVC	6.0	50	80	Open hole	T
354359078403104	MW–2D	4/19/2001	359.77	PVC	6.0	81	601	Open hole	B
354404078403101	MW–3S	5/10/2001	375.02	PVC	4.0	20	35	0.01 slotted PVC	R
354404078403102	MW–3I	5/14/2001	375.49	PVC	4.0	45	60	0.01 slotted PVC	I
354404078403103	MW–3D	5/16/2001	376.35	PVC	6.0	66	301	Open hole	B
354401078403401	PW–1	6/14/2001	358.07	Galv. Steel	6.0	62.5	302	Open hole	B
354400078403401	PZ–1	6/20/2001	354.87	PVC	2.0	30	50	0.01 slotted PVC	R
354402078403401	PZ–2	6/20/2001	359.09	PVC	2.0	17	37	0.01 slotted PVC	R
354400078403301	PZ–3	5/15/2003	358.83	PVC	2.0	32	47	0.01 slotted PVC	R
0208762750	Unnamed tributary	4/1/2002	326.87	na	na	na	na	na	SW

[a]Zone isolated from the open borehole using a single packer (UZ, upper zone; LZ, lower zone).

[b]Depth of packer.

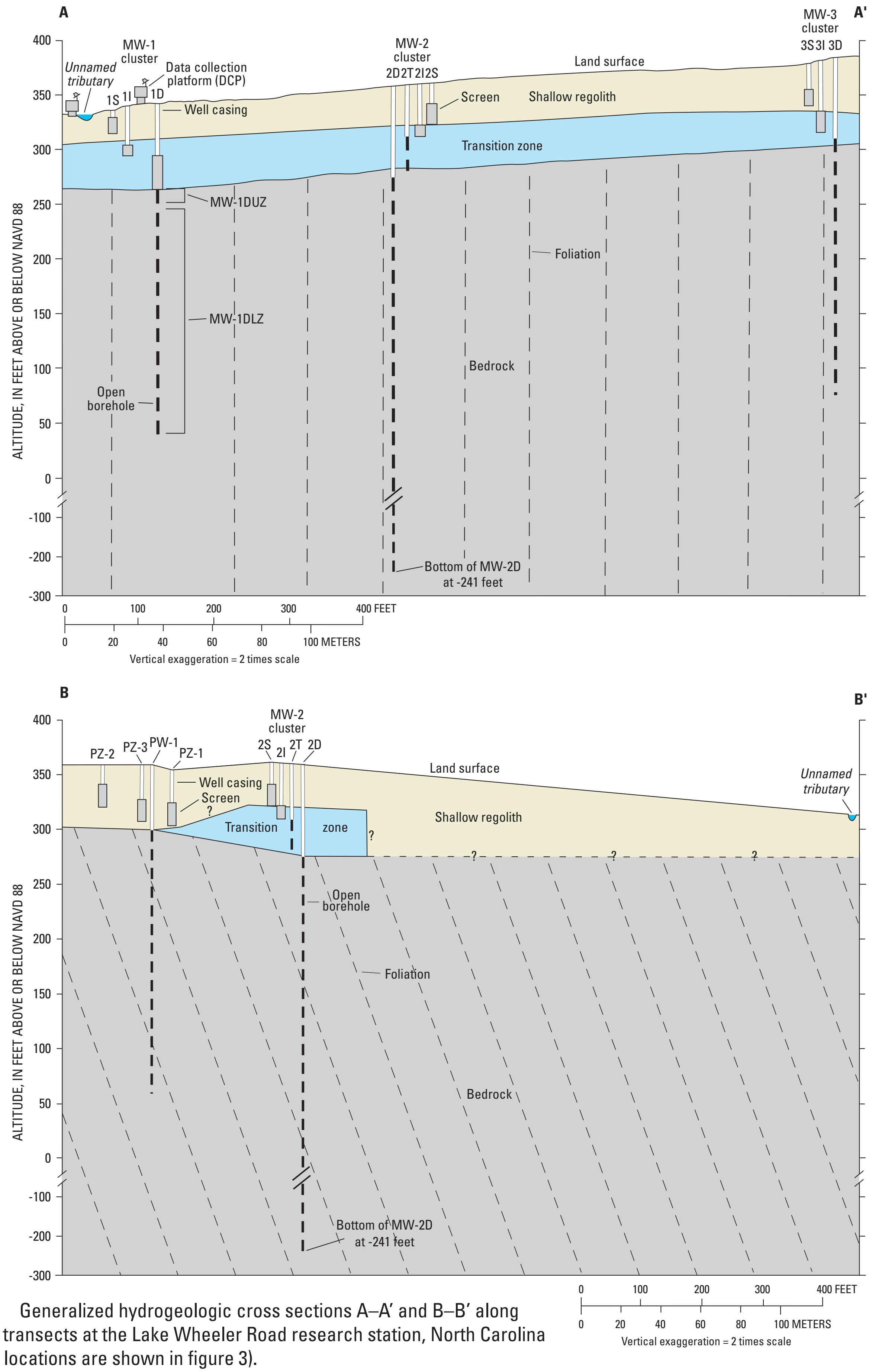

Figure 4. Generalized hydrogeologic cross sections A–A′ and B–B′ along the well transects at the Lake Wheeler Road research station, North Carolina (section locations are shown in figure 3).

Water-Resources Data

Borehole geophysical logs were collected from all four bedrock wells and the transition-zone well MW–2T at the LWRRS. Data collected from these wells include caliper and natural gamma logs, short-normal and long-normal resistivity logs, fluid-temperature and fluid-resistivity logs, heat-pulse flowmeter data (both ambient and pumping conditions), and OTV images (figs. 5–10).

Monthly water levels have been measured in all 14 wells at the LWRRS since July 2001 except well PZ–3, which has been measured since May 2003 (fig. 11). The period of record discussed in this report is from July 2001 through September 2004. Ground-water altitudes at well cluster MW–1 ranged from about 332 to 334 ft in the shallow and transition zones and about 333 to 336 ft in the bedrock zone. The water-level altitudes in the bedrock zone were consistently higher than water-level altitudes in the shallow and transition zones at well cluster MW–1. Ground-water altitudes at well cluster MW–2 ranged from about 331 to 335 ft in the shallow and transition zones and from about 328 to 330 ft in the bedrock zone. The water-level altitudes in the bedrock zone were consistently lower than water-level altitudes in the shallow and transition zones at well cluster MW–2. Ground-water altitudes at well cluster MW–3 ranged from about 348 to 352 ft in all three zones. The water-level altitudes in the shallow zone were consistently lower than water-level altitudes in the transition and bedrock zones at well cluster MW–3. Ground-water altitudes in the well PW–1 ranged from about 334 to 337 ft. Ground-water altitudes in the piezometers ranged from about 340 to 343 ft in PZ–1 and PZ–3, and from about 344 to 348 ft in PZ–2. Detailed summaries of ground-water-level data recorded in the LWRRS wells for water years 2001–04 are published in USGS annual data reports for North Carolina (Howe and others, 2002, 2003, 2004, and 2005).

Continuous ground-water levels were recorded in five wells, and stage was recorded in a nearby stream (unnamed tributary to Swift Creek, station 0208762750). Ground-water levels were recorded hourly in all three wells in cluster MW–1 from December 2001 to June 2004 (fig. 12) and in bedrock wells MW–2D from May to September 2003 and MW–3D from February to September 2003 (fig. 13). Stage in the unnamed tributary was recorded at 15-minute intervals from April 2002 to September 2004. For purposes of comparison to well cluster MW–1, continuous stage in the unnamed tributary was plotted hourly from April 2002 to June 2004 (fig. 12).

Slug tests were conducted at the LWRRS in October 2001 and February 2003 (Chapman and others, 2005). A 5-ft long, 3-inch or a 3-ft long, 1.5-inch diameter PVC bailer or a 5-ft long, 2.5-inch diameter solid PVC slug was used to displace water in the wells. The slug tests were conducted to obtain estimates of hydraulic conductivity in the aquifer zones tapped by the wells—the regolith, transition zone, and bedrock. The estimates obtained are representative of conditions in the immediate vicinity of the tested wells. The wells and intervals tested, and the hydraulic conductivity values are listed in table 2.

Table 2. Analytical results of slug tests in wells at the Lake Wheeler Road research station, North Carolina.

Well number	Screened/open interval (feet below land surface)	Hydraulic conductivity (feet per day)
Regolith wells		
MW–1S	5–20	0.8
MW–2S	20–40	0.6
MW–3S	20–35	3.0
PZ–1	30–50	1.0
PZ–2	17–37	4.0
Transition-zone wells		
MW–1I	31.5–41.5	1.2
MW–2I	40–50	0.5
MW–3I	45–60	0.7
MW–2T	50–80	0.2
Bedrock wells		
MW–1D	47–302	0.3
MW–2D	81–60	1.1
MW–3D	66–301	0.04
PW–1	62.5–302	0.05

Water-quality samples were collected from the unnamed tributary and all wells (excluding PZ–1, PZ–2, and PZ–3) at the LWRRS. To date (2006), five sets of water-quality samples have been collected from well cluster MW–1, four sets each from well clusters MW–2 and MW–3 and from well PW–1, and three sets from the unnamed tributary. Water-quality-data results are displayed in Piper diagrams for all sampling dates (fig. 14) and in Stiff diagrams for May 2002 (fig. 15). Major ion geochemistry in periodic ground-water-quality samples from the shallow and transition-zones and in the unnamed tributary samples is shown in figure 14A; major ion geochemistry in ground-water samples from the open-borehole bedrock wells at the LWRRS is shown in figure 14B. Ranges of water-quality-data results for all sampling dates are displayed in box plots (figs. 16–18).

Continuous water-quality data were collected in four zones in the MW–1 cluster and in the unnamed tributary. Hourly data from wells MW–1S (shallow regolith), MW–1I (transition zone), and MW–1D (bedrock) were collected from December 2001 to June 2004 (figs. 19–21). An inflatable packer was installed in MW–1D to isolate a shallow fracture zone within the transition zone (MW–1DUZ; fig. 22) from July 2002 to November 2003. Fifteen-minute data were collected to measure temperature, pH, SC, and DO concentrations in the unnamed tributary from April 2002 to June 2004 (fig. 23). Water temperature at well cluster

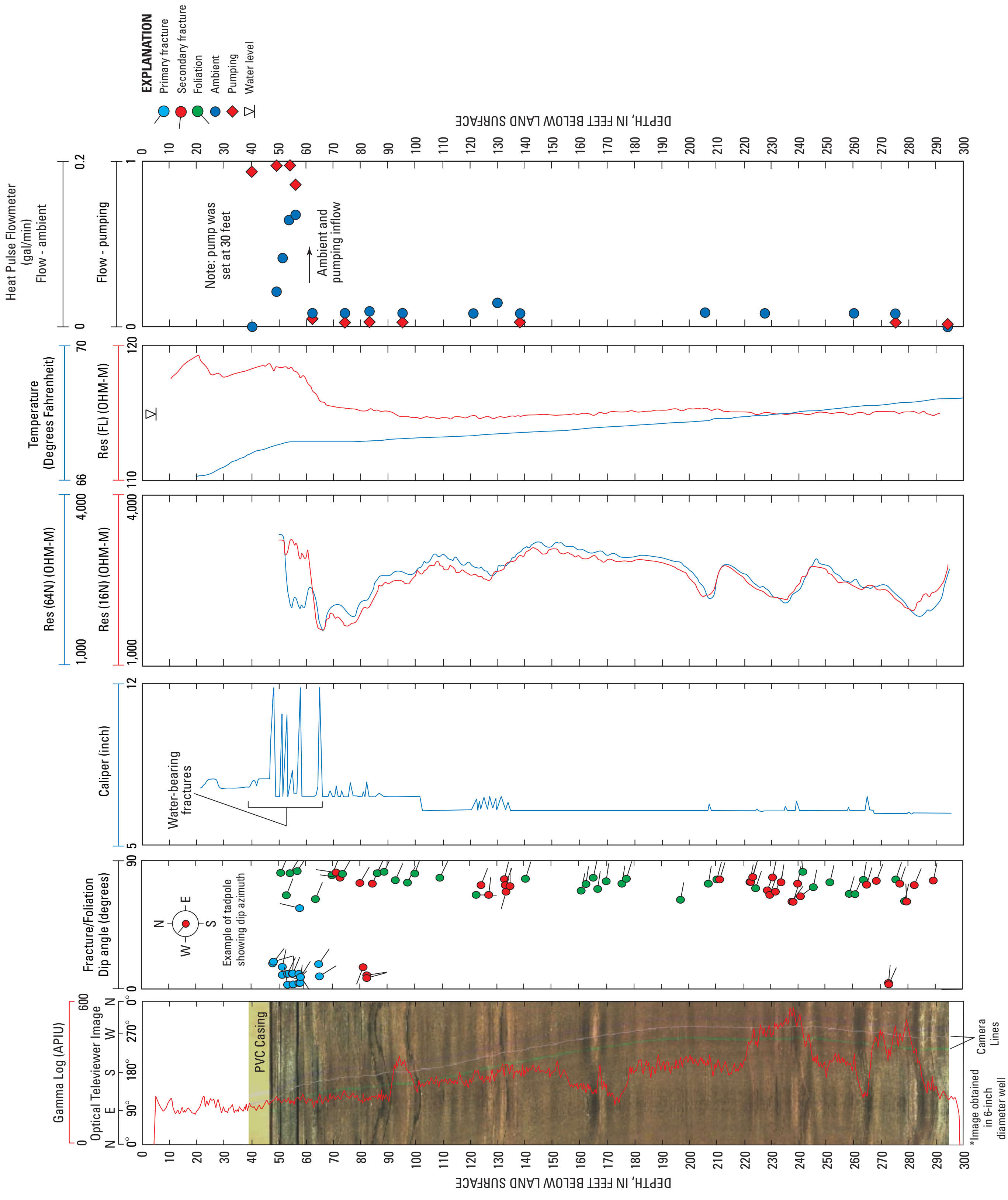

Figure 5. Geophysical logs of bedrock well MW–1D at the Lake Wheeler Road research station, North Carolina.

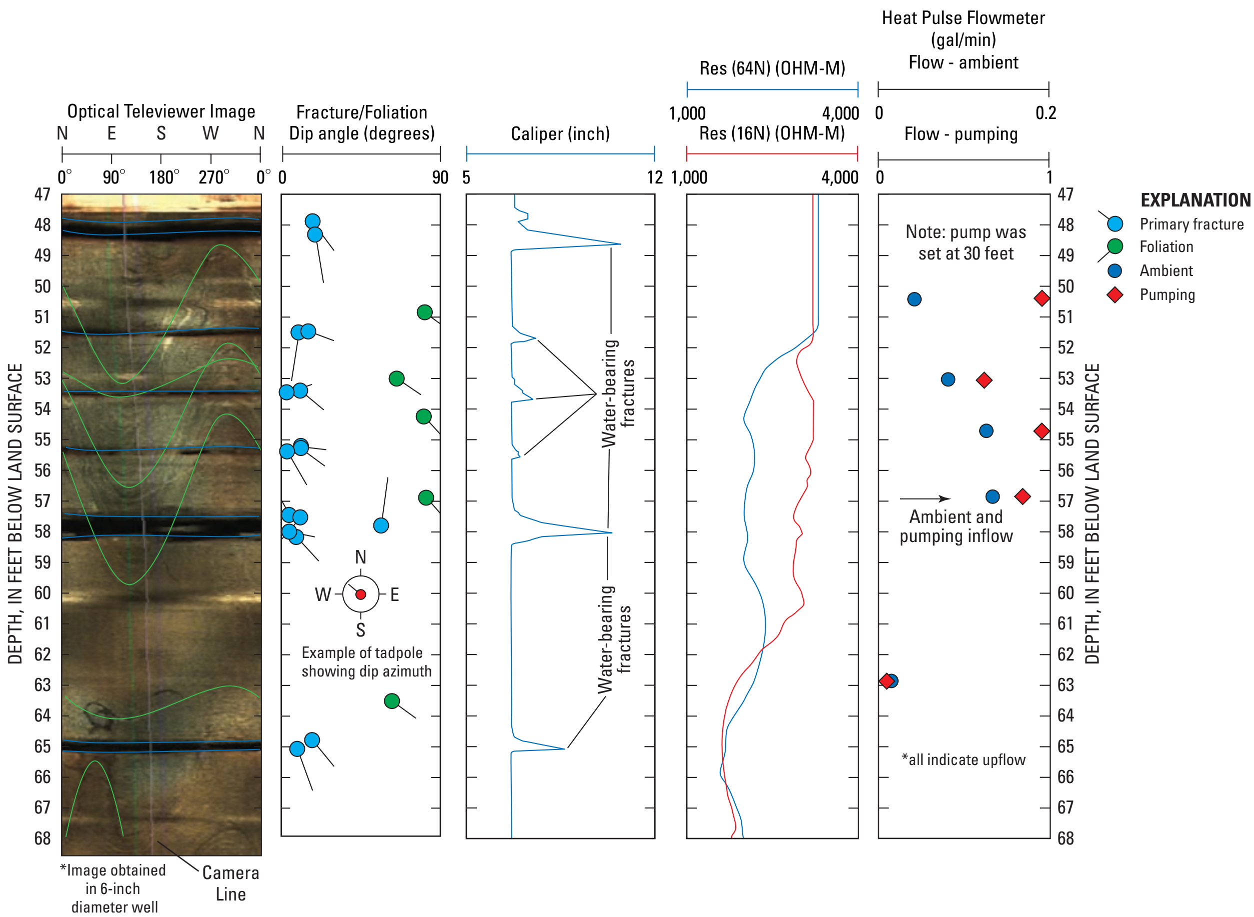

Figure 6. Geophysical logs of transition-zone fractures (MW–1DUZ) in well MW–1D at the Lake Wheeler Road research station, North Carolina.

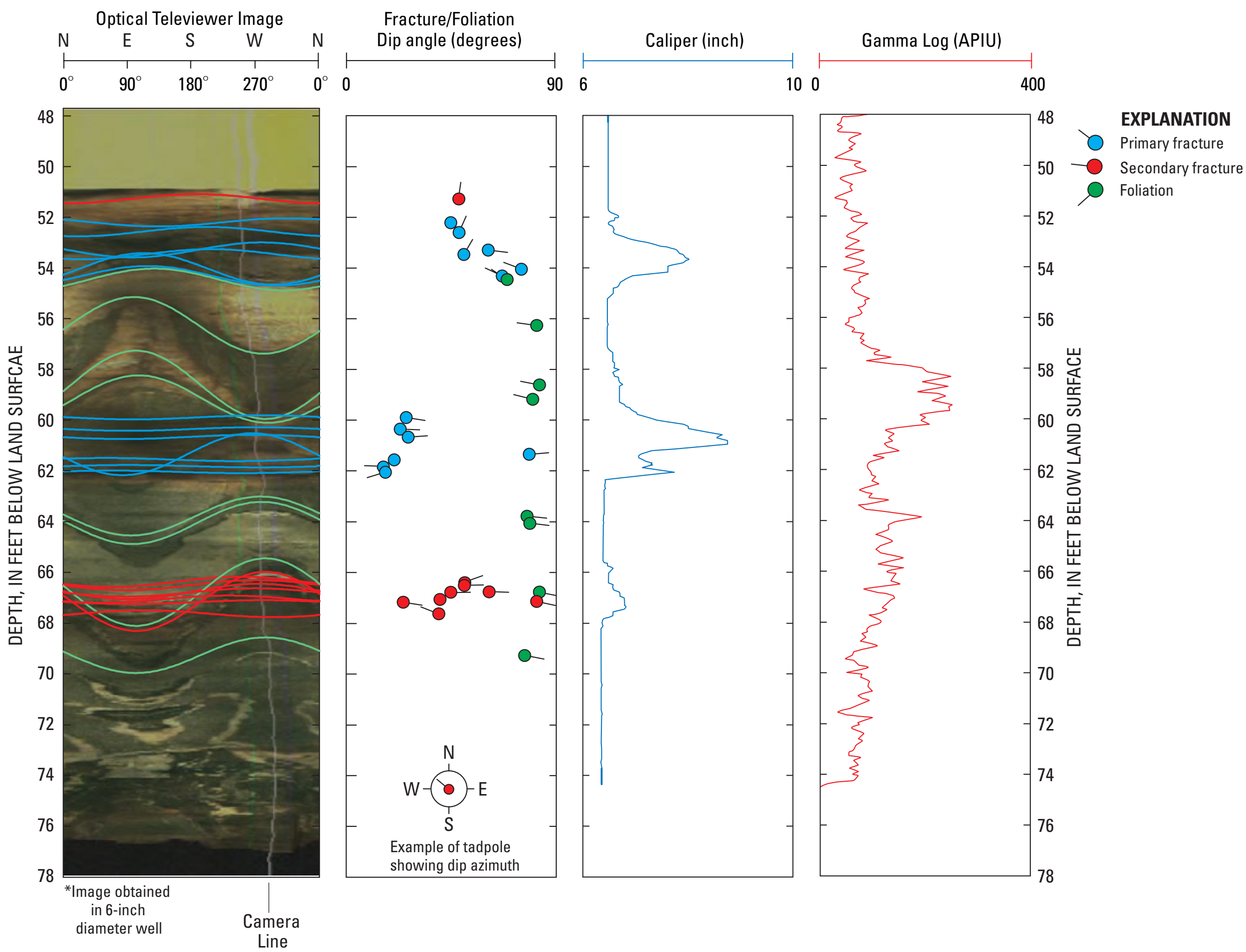

Figure 7. Geophysical logs of transition-zone well MW–2T at the Lake Wheeler Road research station, North Carolina.

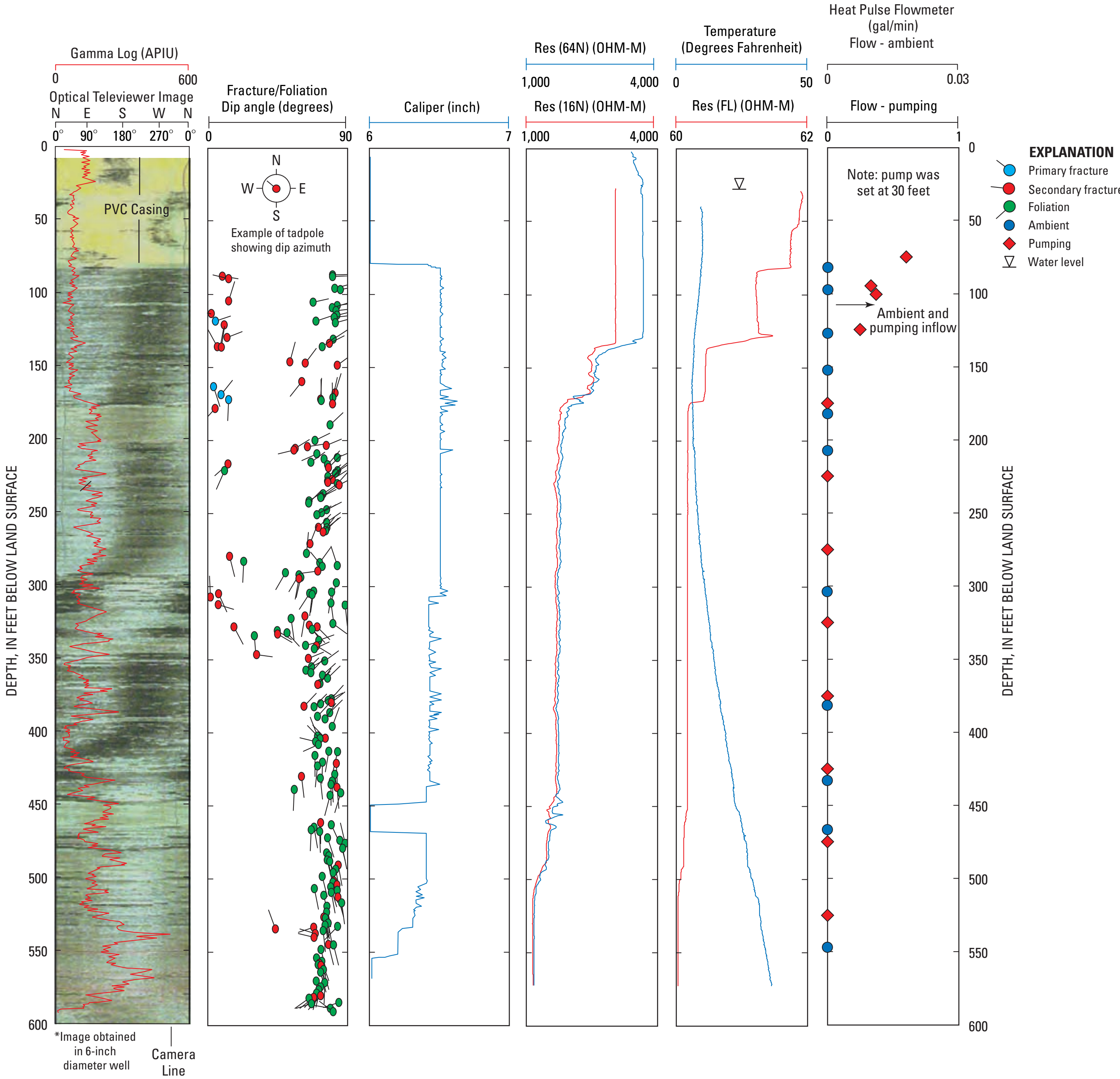

Figure 8. Geophysical logs of bedrock well MW–2D at the Lake Wheeler Road research station, North Carolina.

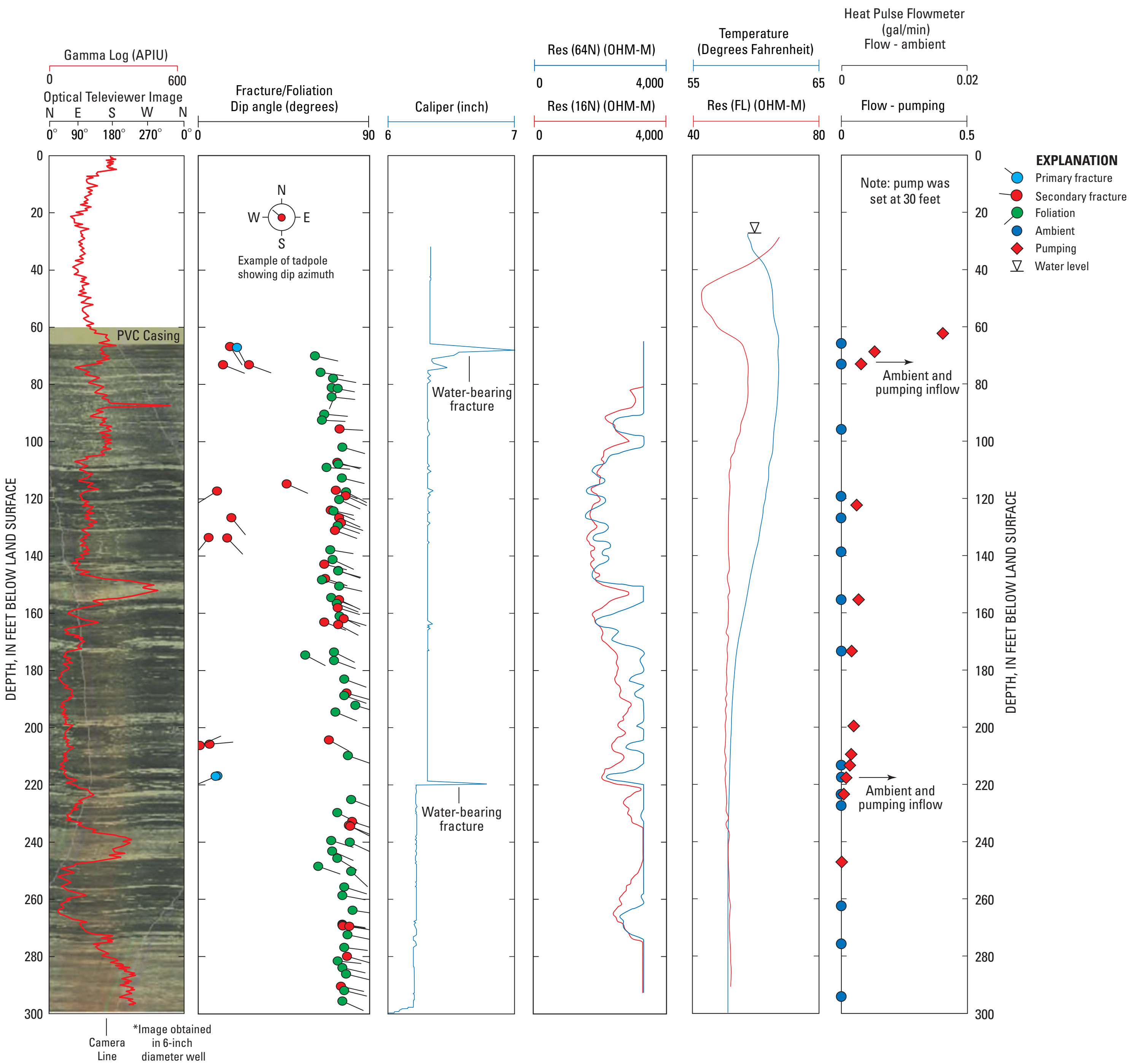

Figure 9. Geophysical logs of bedrock well MW–3D at the Lake Wheeler Road research station, North Carolina.

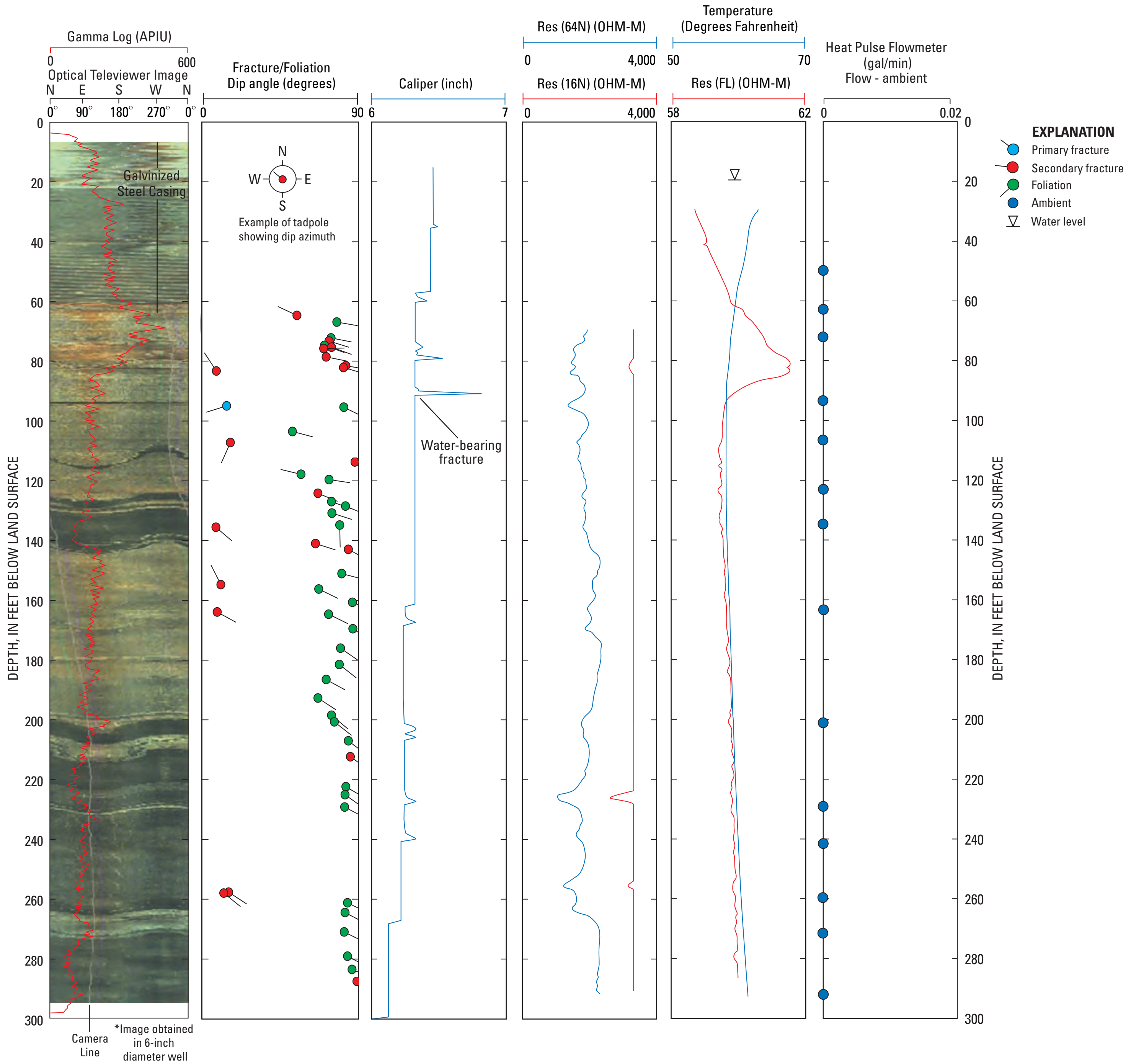

Figure 10. Geophysical logs of bedrock well PW–1 at the Lake Wheeler Road research station, North Carolina.

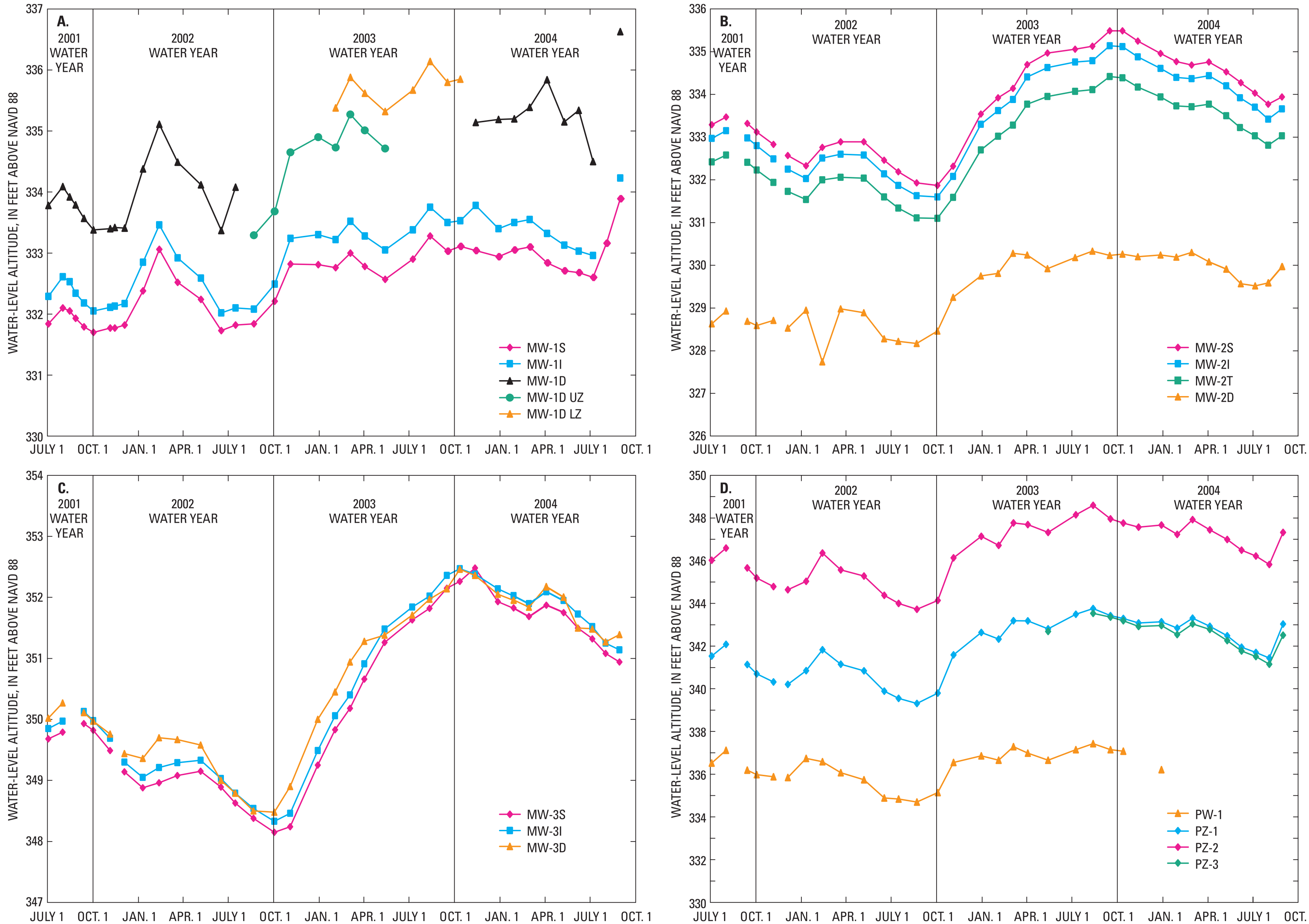

Figure 11. Periodic ground-water levels recorded in well clusters (A) MW–1, (B) MW–2, (C) MW–3, and (D) the aquifer-test well and piezometers at the Lake Wheeler Road research station, North Carolina.

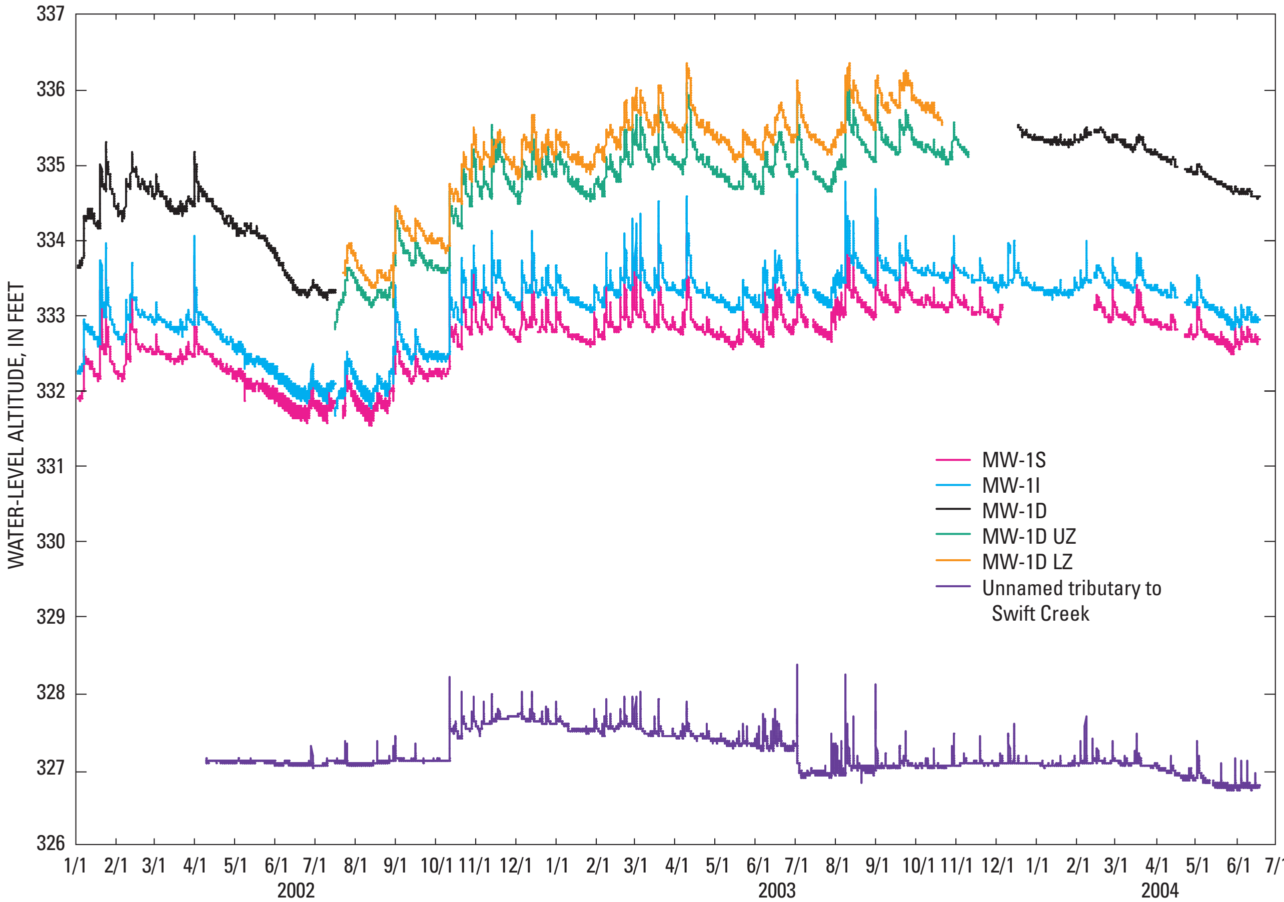

Figure 12. Hourly ground-water levels recorded in well cluster MW–1 and hourly stage recorded at the tributary site at the Lake Wheeler Road research station, North Carolina.

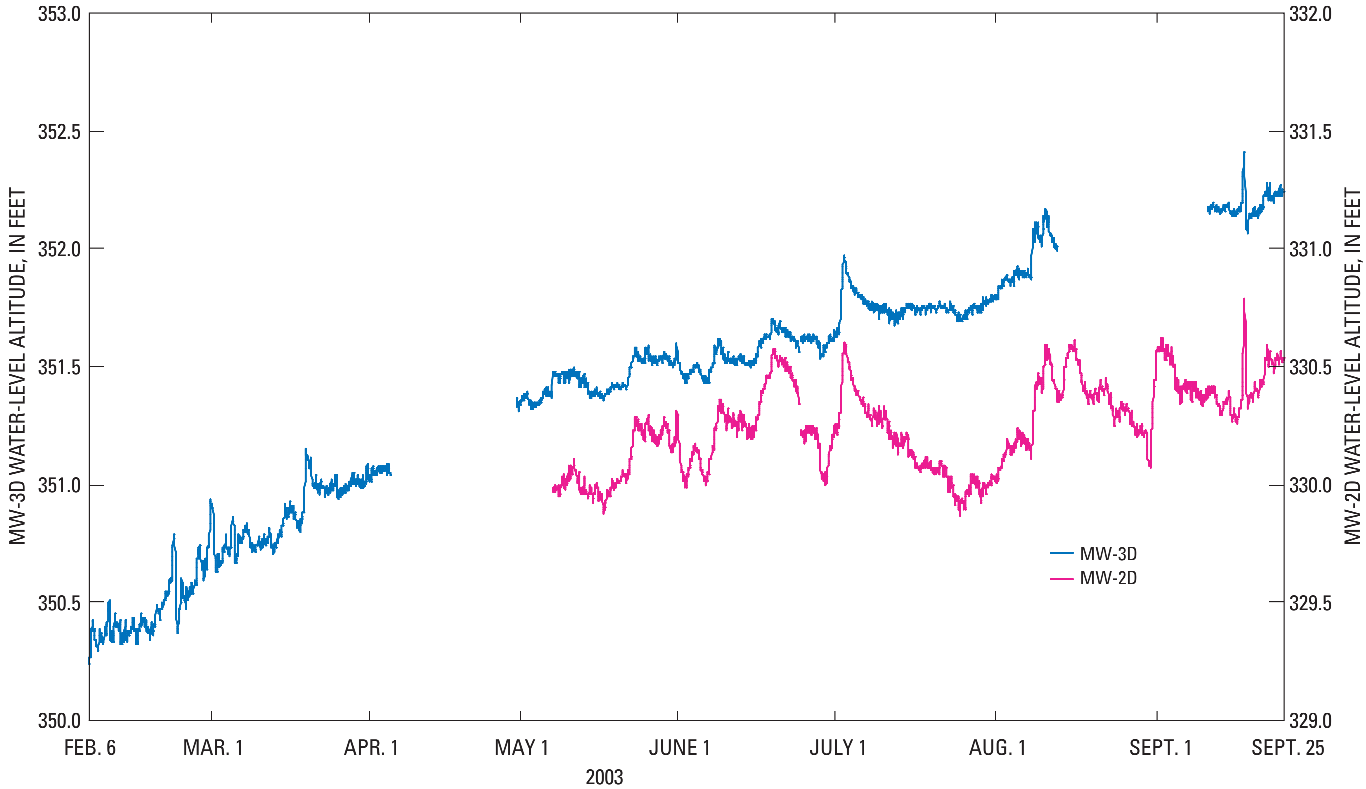

Figure 13. Hourly ground-water levels recorded in bedrock wells MW–2D and MW–3D at the Lake Wheeler Road research station, North Carolina.

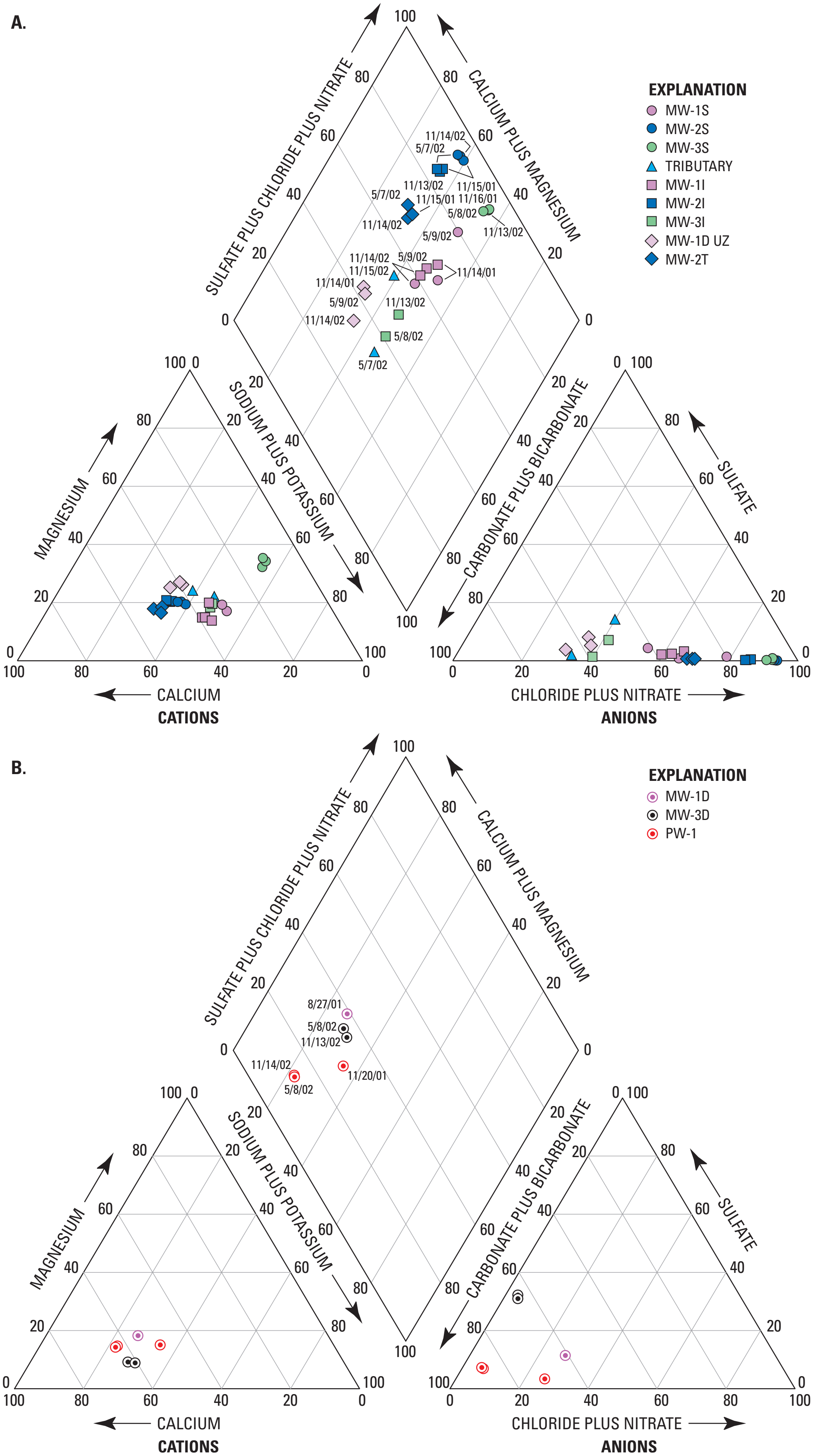

Figure 14. The water chemistry of samples from (A) regolith and transition-zone wells and the tributary site, and (B) bedrock wells at the Lake Wheeler Road research station, North Carolina.

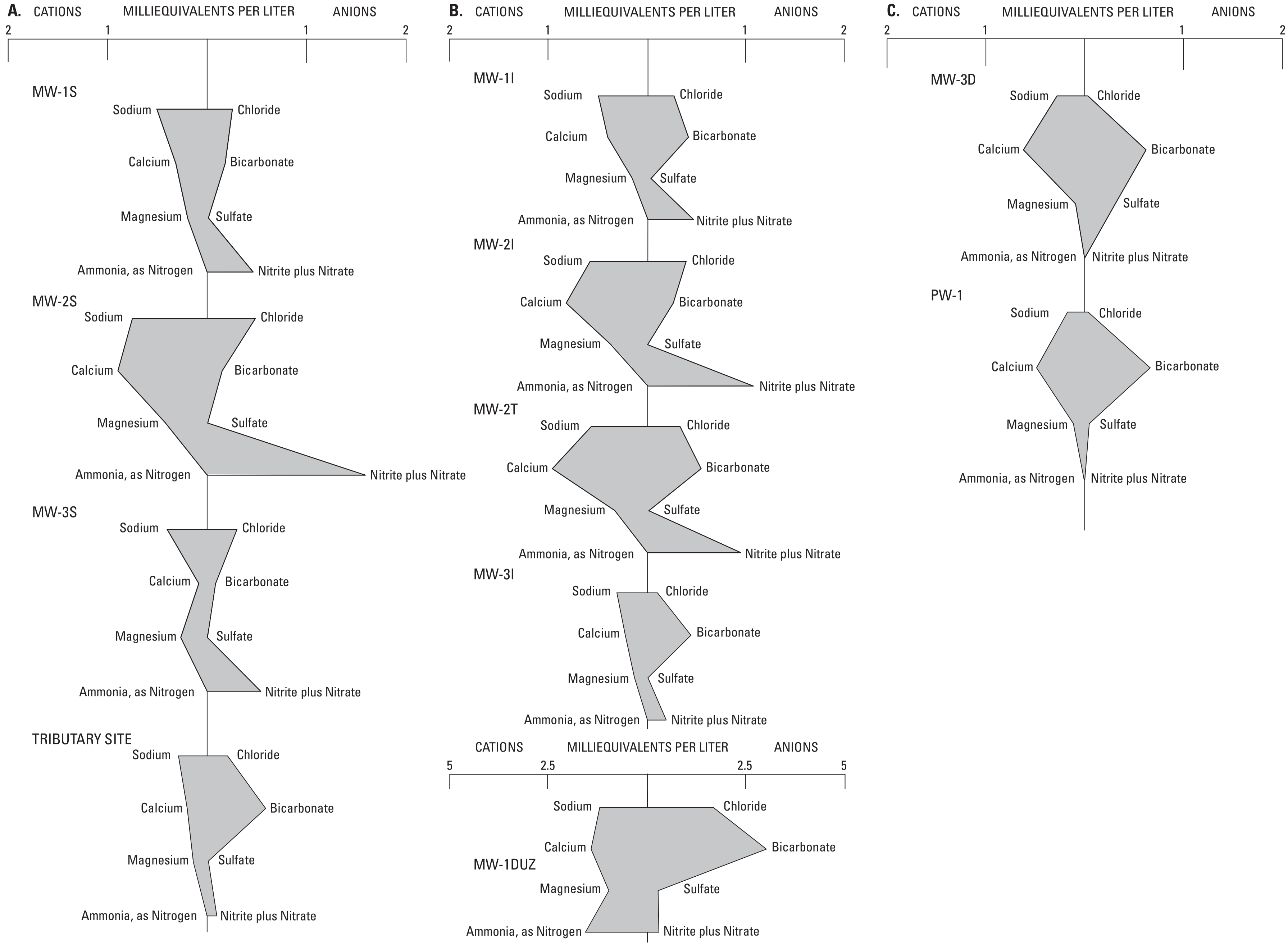

Figure 15. Major ion milliequivalents in water samples collected from (A) regolith wells and the tributary site, (B) transition-zone wells, and (C) open-borehole bedrock wells at the Lake Wheeler Road research station, North Carolina, May 2002.

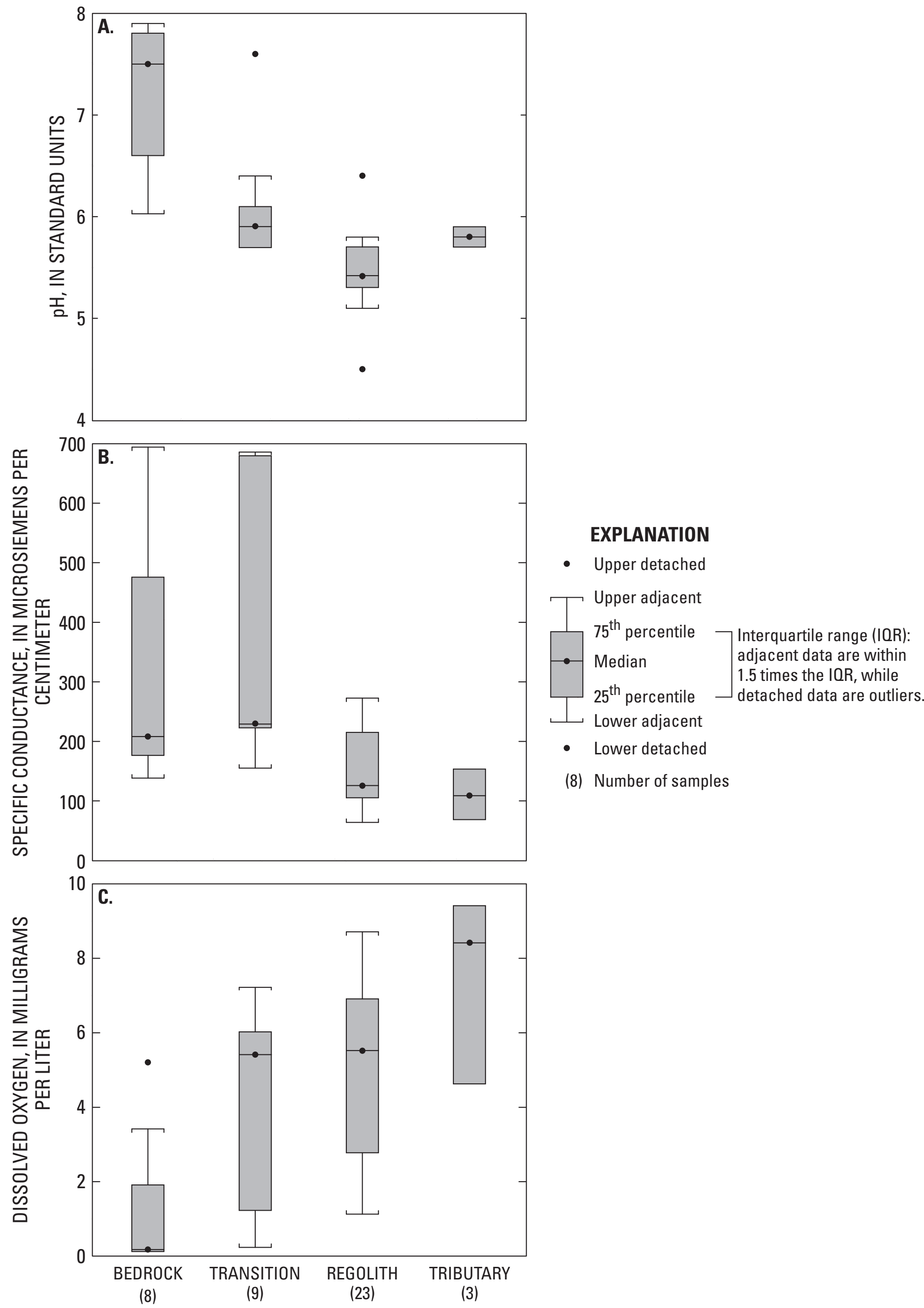

Figure 16. The range, median, and quartile statistical values for (A) pH, (B) specific conductance, and (C) dissolved oxygen for wells and the tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.

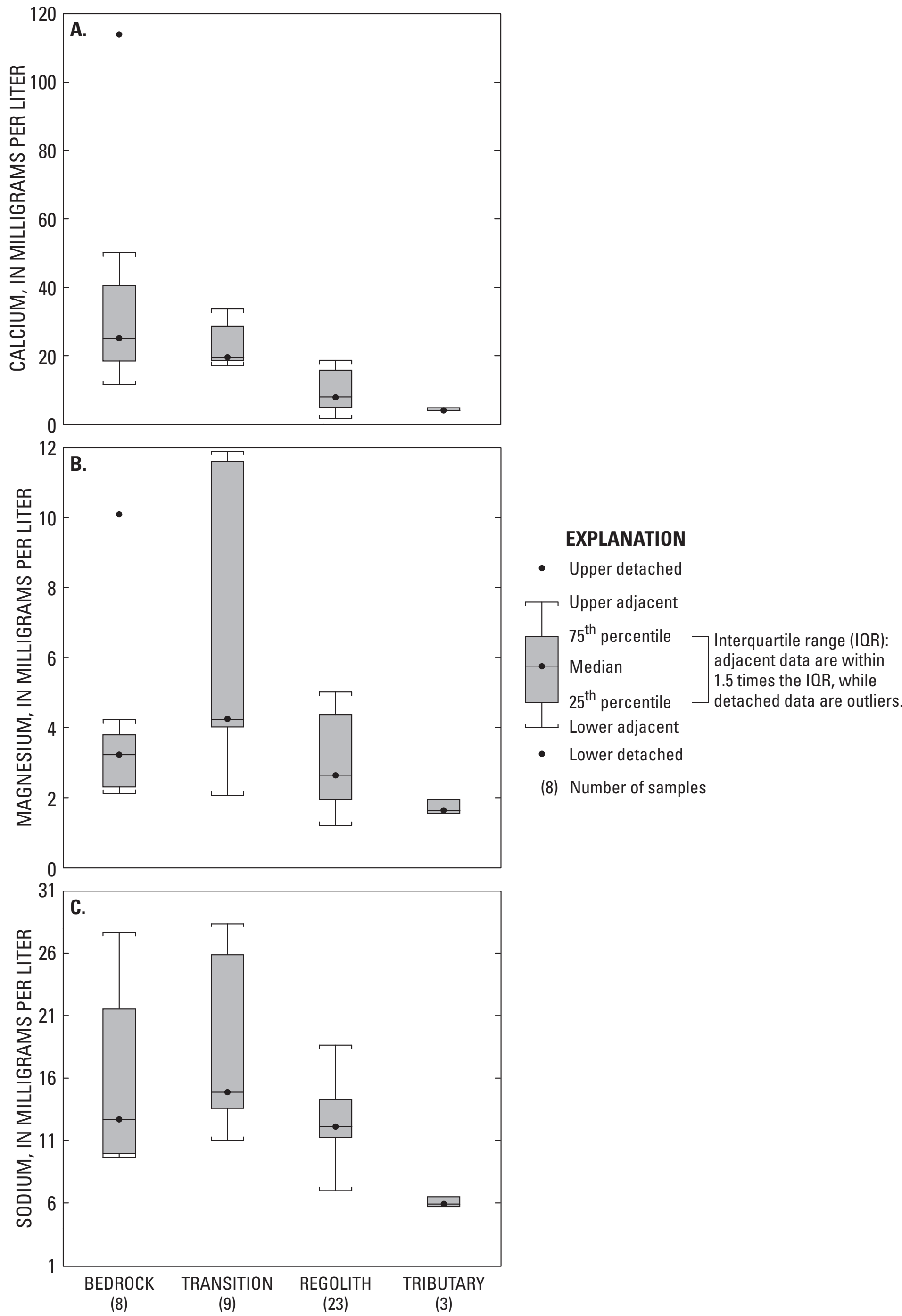

Figure 17. The range, median, and quartile statistical values for (A) calcium, (B) magnesium, and (C) sodium for wells and the tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.

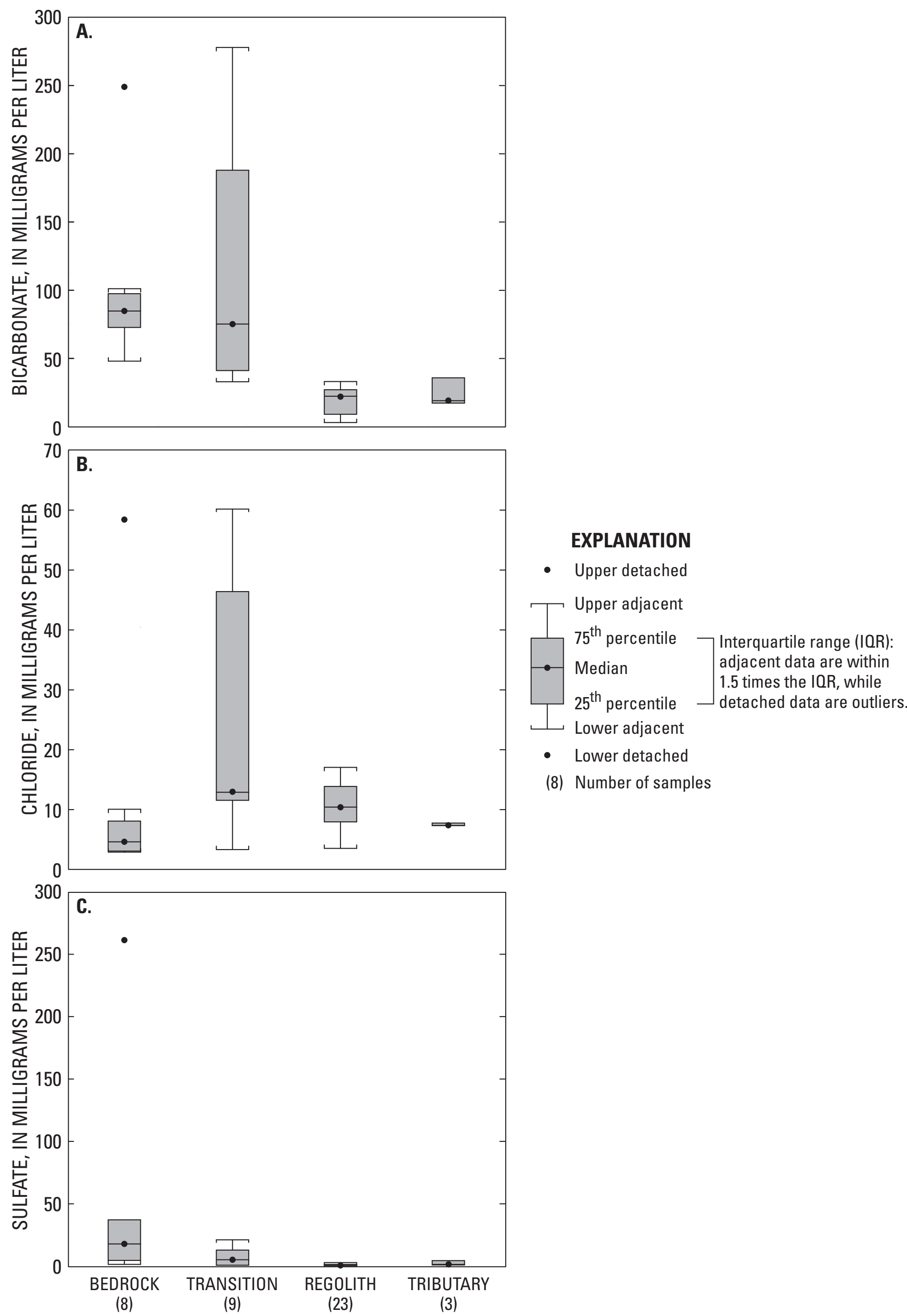

Figure 18. The range, median, and quartile statistical values for (A) bicarbonate, (B) chloride, and (C) sulfate for wells and the tributary site during periodic sampling events at the Lake Wheeler Road research station, North Carolina.

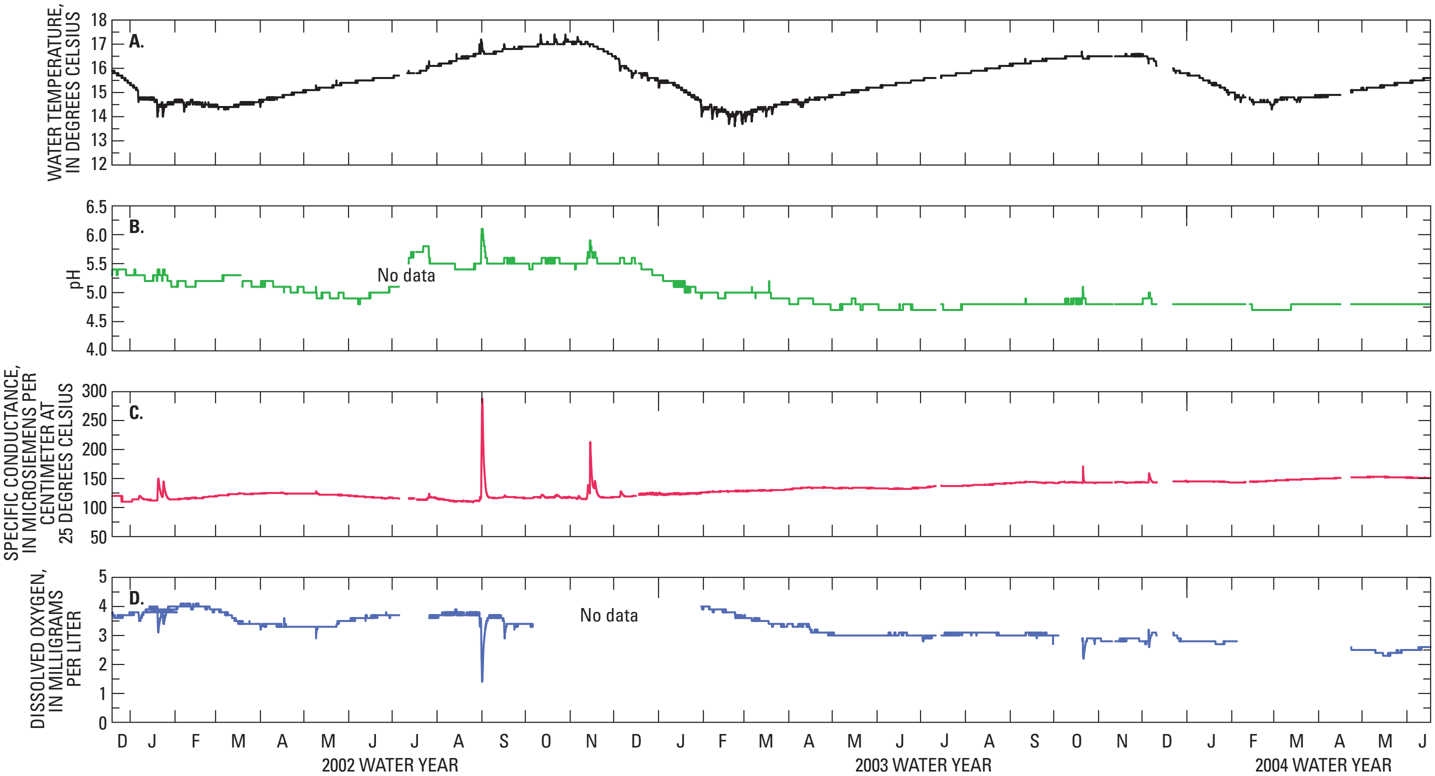

Figure 19. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–1S in the shallow regolith at the Lake Wheeler Road research station, North Carolina, December 2002 through June 2004.

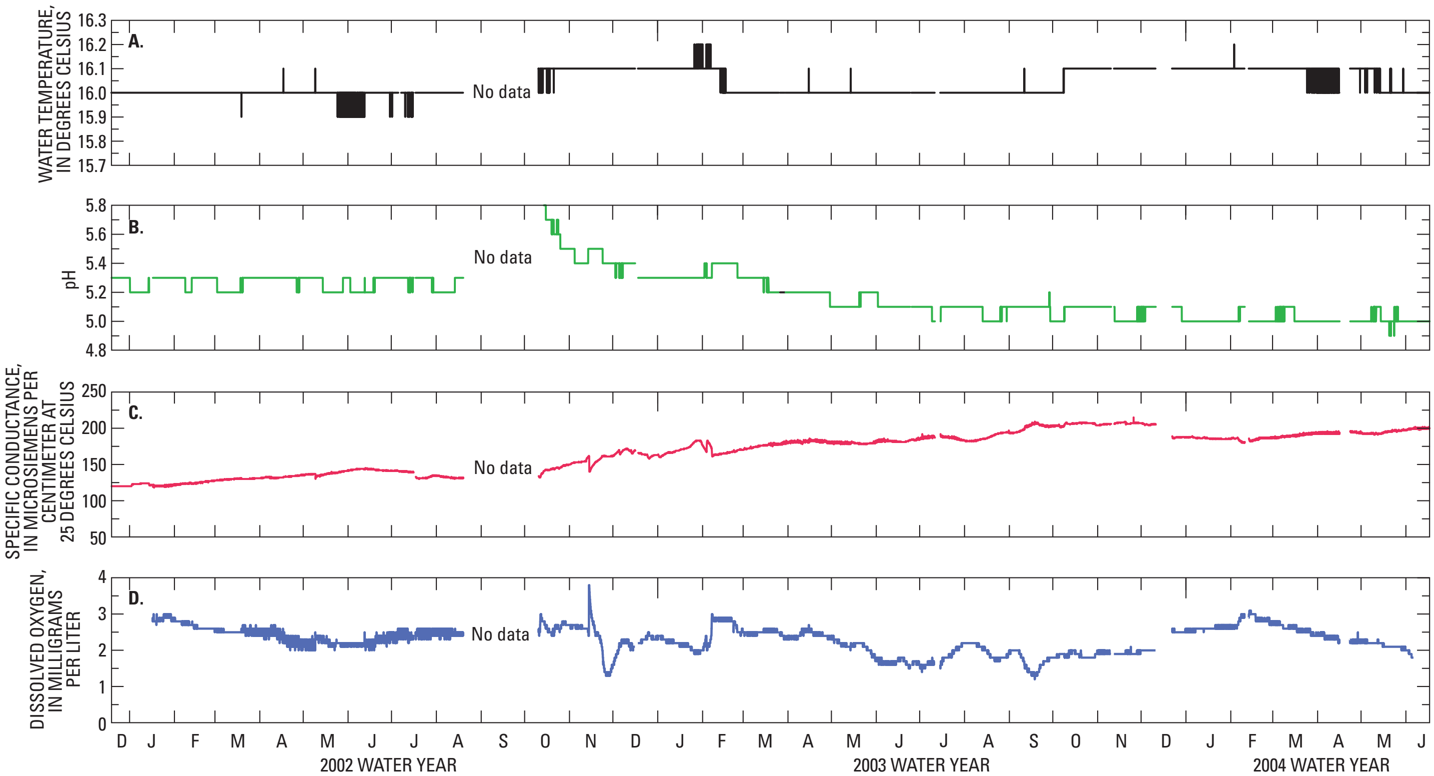

Figure 20. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–1I in the transition zone at the Lake Wheeler Road research station, North Carolina, December 2002 through June 2004.

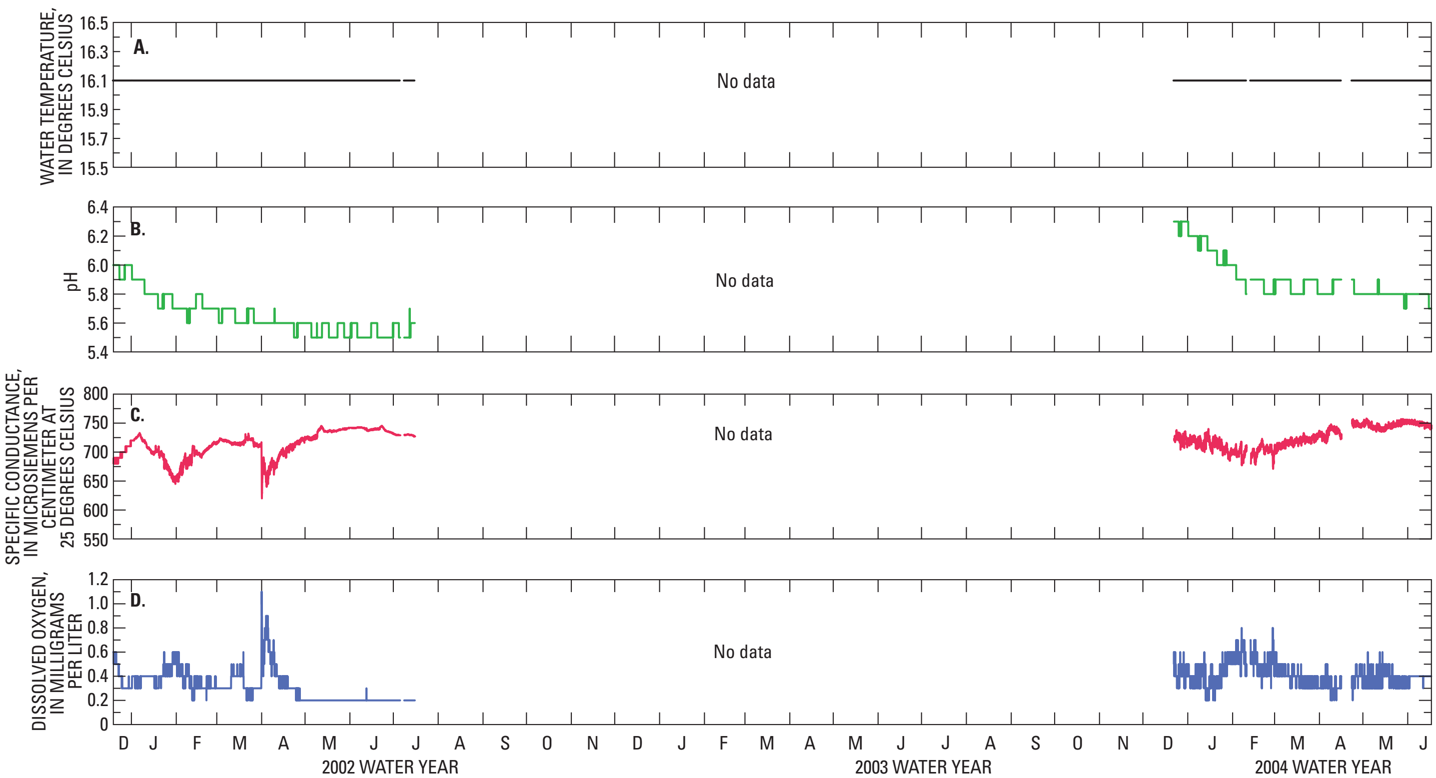

Figure 21. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–1D in the bedrock at the Lake Wheeler Road research station, North Carolina, December 2002 through June 2004 (packer was installed in July 2002; see figure 22 for missing data).

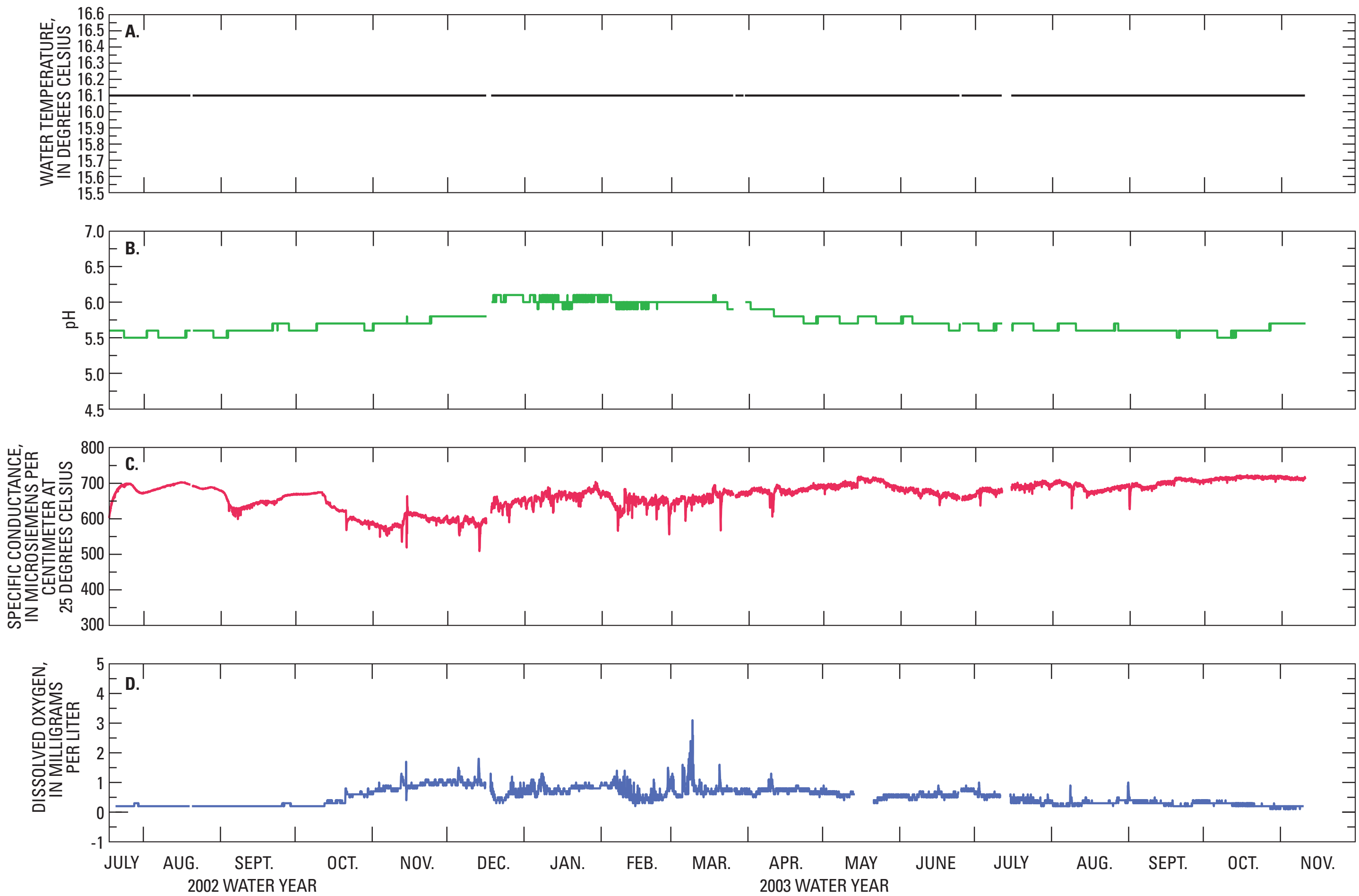

Figure 22. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–1DUZ during installation of an inflatable packer at the Lake Wheeler Road research station, North Carolina, July 2002 through November 2003.

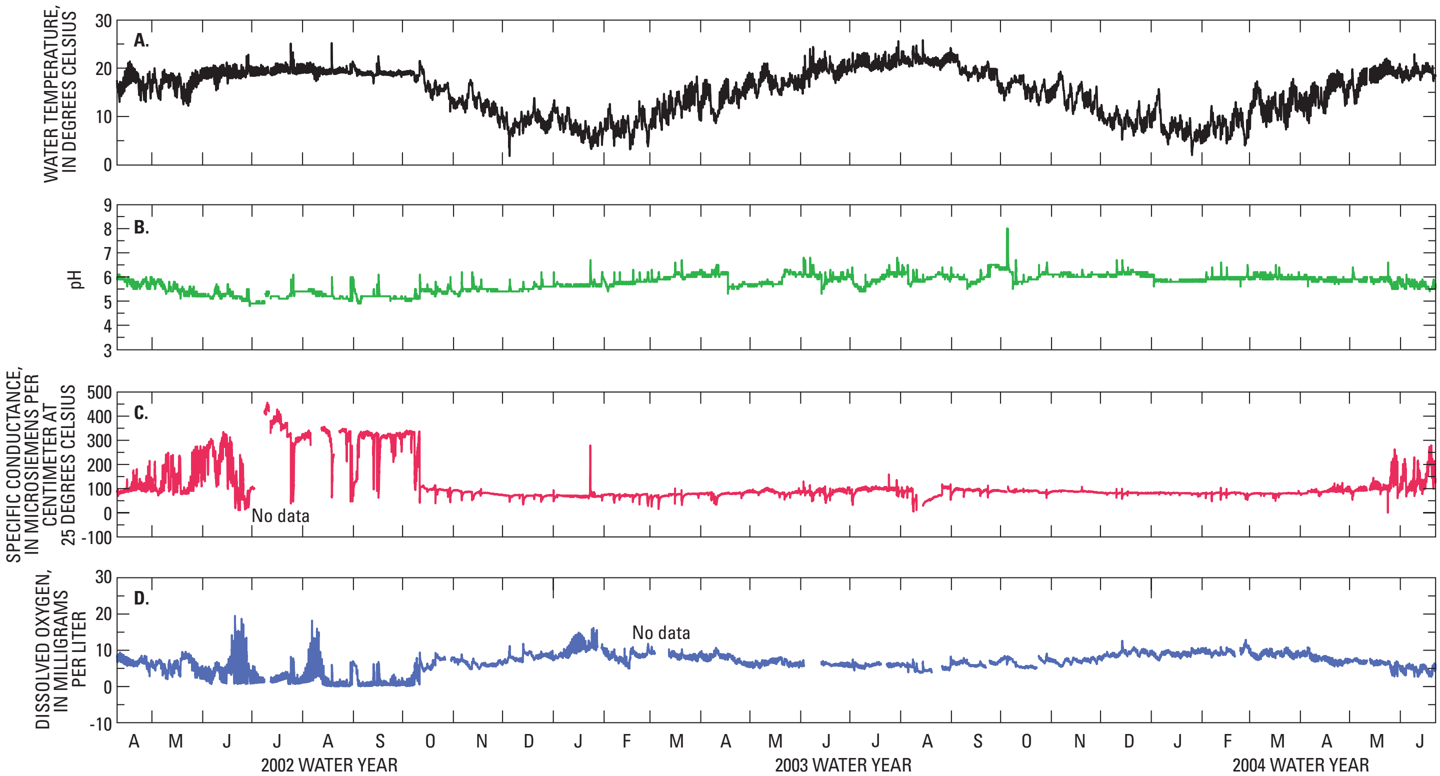

Figure 23. Fifteen-minute record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in the unnamed tributary at the Lake Wheeler Road research station, North Carolina, April 2002 through June 2004.

MW–1 ranged from about 14 to 17 degrees Celsius (°C) in the shallow zone, from about 16 to 16.1 °C in the transition zone, and was a steady 16.1 °C in the bedrock zone. Specific conductance ranged from about 100 to 150 microsiemens per centimeter (μS/cm) at 25 °C in the shallow zone, from about 125 to 200 μS/cm in the transition zone, and from about 650 to 750 μS/cm in the bedrock zone. The pH ranged from about 5 to 5.5 in the shallow and transition zones, and from about 5.5 to 6.2 in the bedrock zone. Dissolved-oxygen concentrations ranged from about 2 to 4 milligrams per liter (mg/L) in the shallow and transition zones, and from about 0.2 to 1 mg/L in the bedrock zone (figs. 19–22). Water temperature in the unnamed tributary to Swift Creek ranged from 5 to 25 °C, SC ranged from about 50 to 300 μS/cm, pH ranged from about 5 to 6, and DO concentrations ranged from about 2 to 10 mg/L (fig. 23).

Langtree Peninsula Research Station

Site Description and Geology

The first hydrogeologic research station installed in the DWQ Mooresville Region of North Carolina as part of the PMREP is the Langtree Peninsula research station (LPRS) in Iredell County (fig. 24). The LPRS is located on Lake Norman and the Davidson Community College Lake Campus (fig. 25). Lake Norman, a manmade reservoir, borders Langtree Peninsula to the north, west, and south. Work Creek and Davidson Creek border the peninsula to the north and south, respectively (fig. 25). The study area encompasses approximately 7 acres about 3.5 miles southwest of the center of Mooresville, NC (fig. 24).

The LPRS lies in the Charlotte litho-tectonic belt in the Piedmont Physiographic Province and is underlain by quartz diorite and biotite gneiss rock types. Regionally, the LPRS is representative of the intermediate metaigneous (MII) hydrogeologic unit (fig. 24), which represents about 3 percent of the Piedmont and Blue Ridge Provinces in North Carolina (Daniel and Dahlen, 2002). The LPRS was selected to evaluate the effects of quartz diorite and massive (weakly foliated) biotite gneiss rock types with moderate to steeply dipping foliation on ground-water quality, thickness and composition of the regolith, thickness and characteristics of the transition zone, and the development and characteristics of bedrock fractures. Work conducted from September 2000 to September 2004 at the LPRS site included the collection and logging of nine soil and rock cores totaling 645 ft, installation of 18 observation wells grouped into six clusters aligned along two topographic transects (A–A' and B–B', figs. 26, 27, respectively), installation of 12 piezometers for water-level and aquifer-test monitoring, installation of a real-time DCP for continuous monitoring of water levels and water quality in a three-well cluster, monthly collection of water levels, semiannual sampling of wells and the lake, a 48-hour aquifer test, slug tests, and borehole geophysical logs.

Well Construction

Six ground-water monitoring-well clusters, each containing three wells, were constructed in addition to 12 piezometers at the LPRS (fig. 25). The piezometers were assigned the prefix GP (geoprobe) or WL (augured), depending on the method of construction. Well-cluster locations were selected to obtain water-quality and water-level data along topographic transects encompassing areas of recharge and discharge based on conceptual models developed for the slope-aquifer system (LeGrand and Nelson, 2004). Criteria for well locations included topographic setting, accessibility, and site boundaries. During this study, a total of 32 wells (including piezometers) were installed at the LPRS (table 3). Cross section A–A' was constructed along the transect from well cluster MW–3 to well cluster MW–2 (figs. 25, 26). Cross section B–B' was constructed along the transect from well cluster MW–6 to well cluster MW–1 (figs. 25, 27). Well clusters MW–2 and MW–1 are located in a conceptual recharge area, and well clusters MW–3 and MW–6 are located in a discharge area near the lake. The 12 piezometers were installed to provide aquifer-test data and to obtain detailed data to define the two-dimensional ground-water flow within the regolith.

Each well cluster at the LPRS consisted of at least three wells—a shallow well to monitor ground-water conditions in the regolith (except at well cluster MW–4); a transition-zone well to monitor ground-water conditions in partially weathered rock and open fractures near the top of bedrock; and a deeper bedrock well to monitor ground water in the fractured-bedrock aquifer (figs. 26, 27). Well-construction information is provided in table 3. Well MW–3D was abandoned in March 2002 due to casing collapse. Well MW–4S was drilled deeper in February 2002, which created an additional transition-zone well (4IA) at well cluster MW–4. Well MW–6I was abandoned in February 2002 due to well-construction problems, and MW–6IB was installed to replace it. Also, 4-inch-diameter PVC liner casings were installed in bedrock wells MW–1D, MW–4D, and MW–6D in December 2001 because of problems with leaky surface casings. The liners were installed to a depth just below the original 6-inch PVC surface casing and were grouted in place using cement and then sealed at the bottom with a butyl rubber boot.

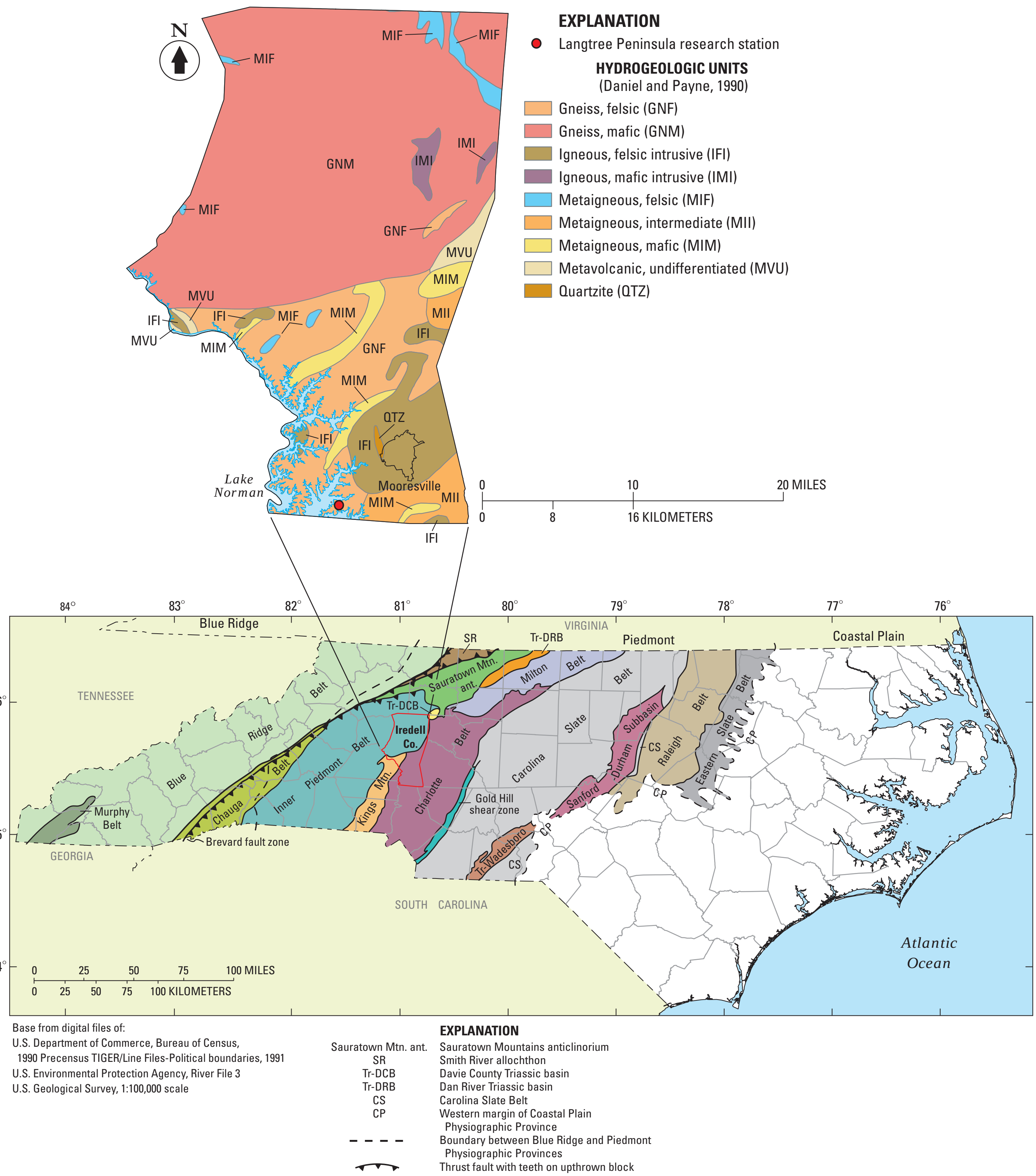

Figure 24. Locations of Langtree Peninsula research station, hydrogeologic units in Iredell County, and geologic belts delineated in North Carolina (modified from North Carolina Geological Survey, 1985; Daniel and Payne, 1990).

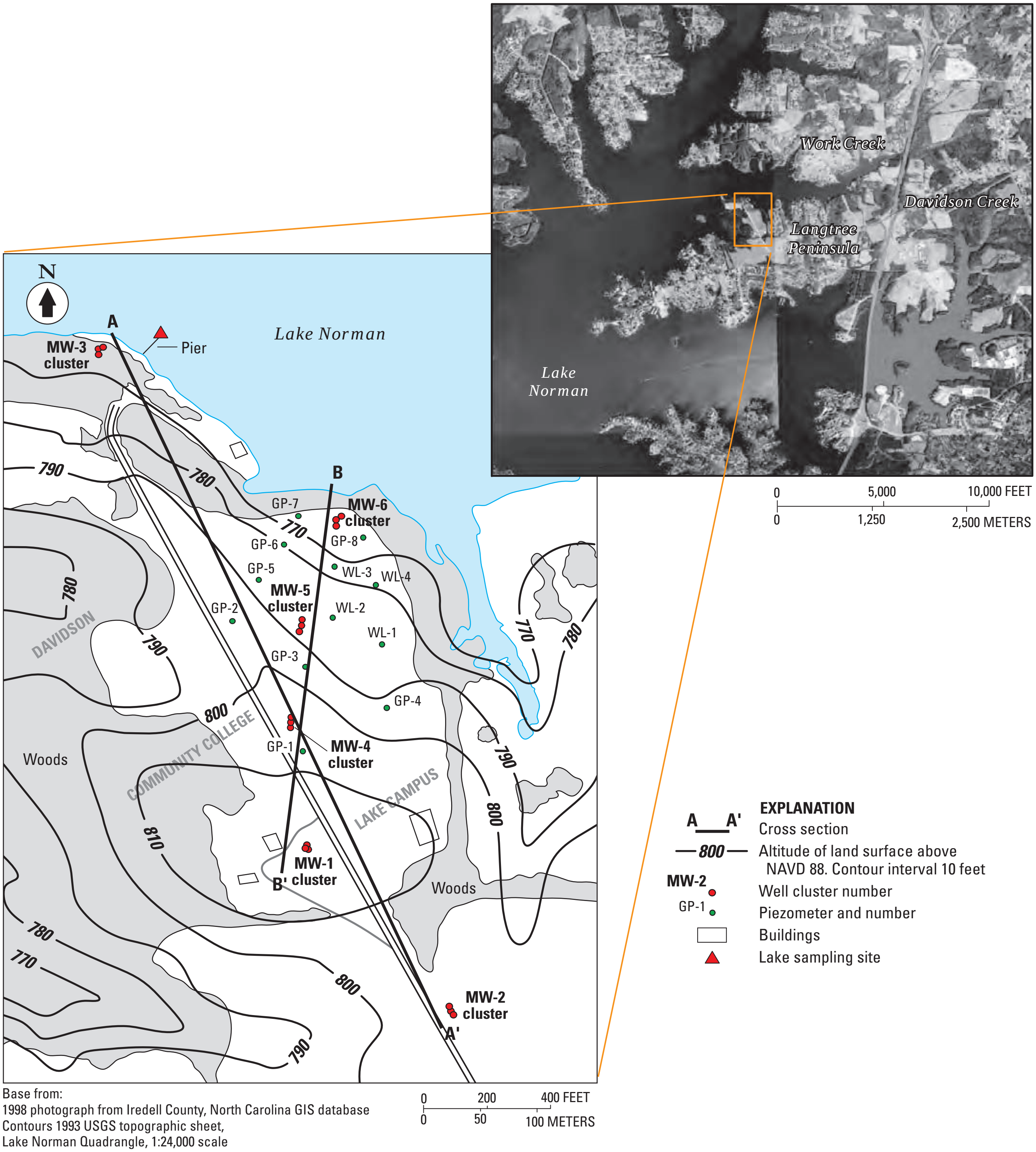

Figure 25. Aerial photograph and topographic map showing locations of well clusters, lake site, and lines of section at the Langtree Peninsula research station in Iredell County, North Carolina.

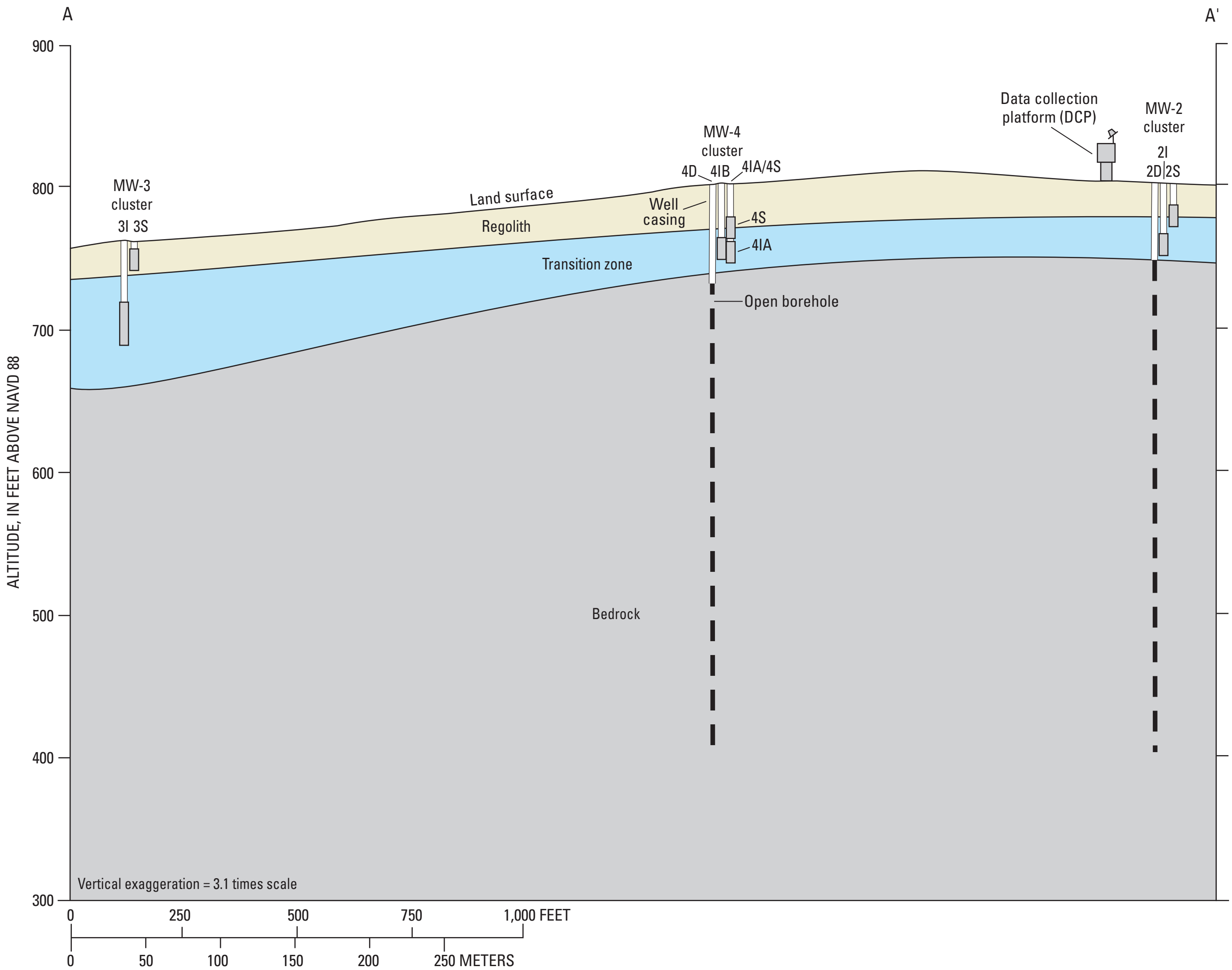

Figure 26. Generalized hydrogeologic cross section A–A′ along the well transect at the Langtree Peninsula research station, North Carolina (section location is shown in figure 25).

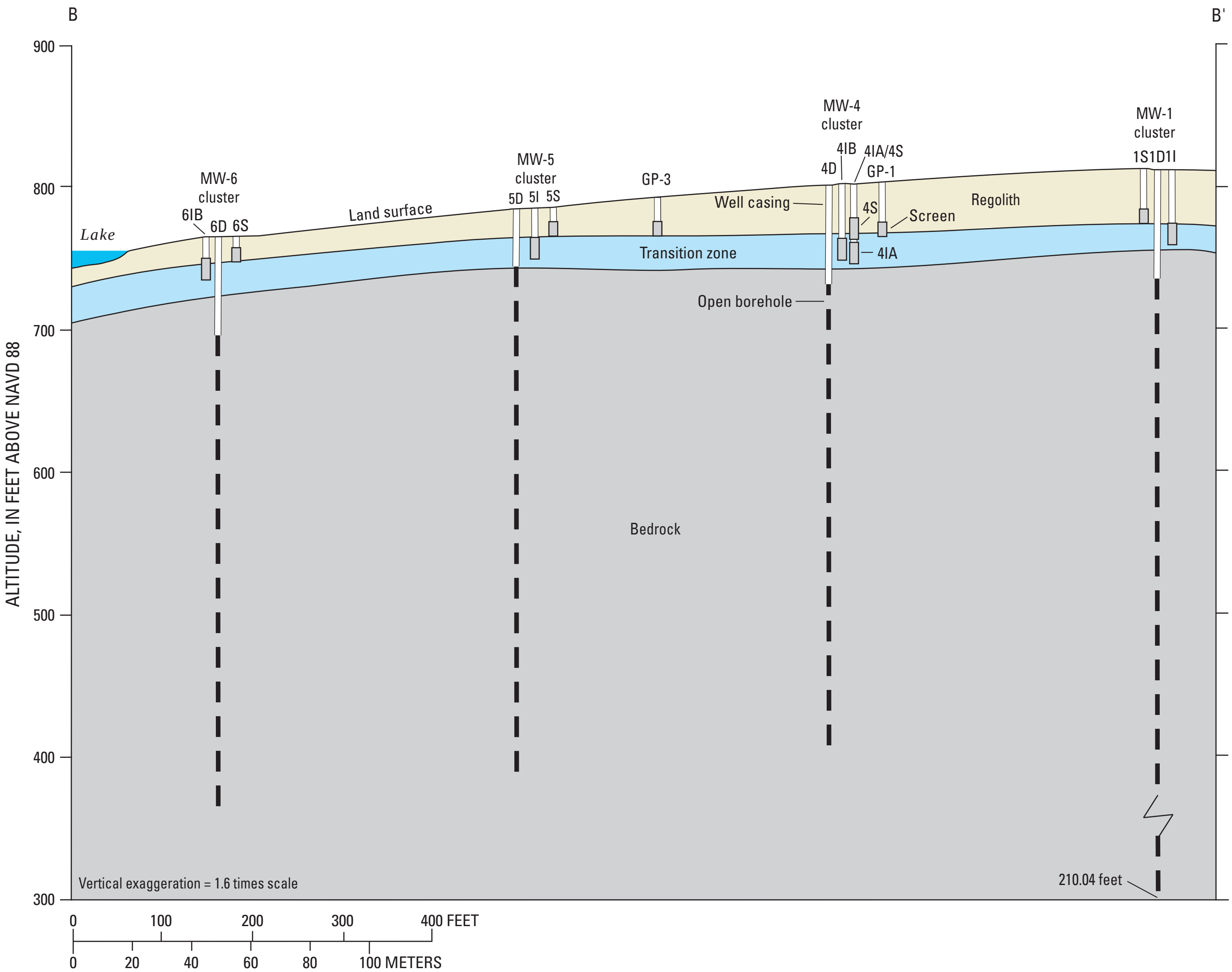

Figure 27. Generalized hydrogeologic cross section B–B′ along the well transect at the Langtree Peninsula research station, North Carolina (section location is shown in figure 25).

Table 3. Construction characteristics of monitoring wells and the surface-water site at the Langtree Peninsula research station, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; MW, monitoring well; S, shallow; PVC, polyvinyl chloride casing; R, regolith; I, transition zone; D, deep; B, bedrock; GP, geoprobe; WL, water level; na, not applicable; SW, surface water]

Site identification	Station name	Construction date	Land-surface altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
						from	to		
353141080524701	MW–1S	10/17/2000	812.57	PVC	4.0	28	38	0.01 slotted PVC	R
353141080524702	MW–1I	10/11/2000	812.65	PVC	4.0	38	53	0.01 slotted PVC	I
353141080524703	MW–1D	11/13/2000	812.51	PVC	4.0	76	602	Open hole	B
353135080524201	MW–2S	12/13/2000	803.08	PVC	4.0	13	28	0.01 slotted PVC	R
353135080524202	MW–2I	12/13/2000	802.89	PVC	4.0	33	48	0.01 slotted PVC	I
353135080524203	MW–2D	11/13/2000	802.69	PVC	6.0	53	400	Open hole	B
353157080525301	MW–3S	1/24/2001	761.96	PVC	4.0	5	15	0.01 slotted PVC	R
353157080525302	MW–3I	1/24/2001	762.92	PVC	4.0	43	73	0.01 slotted PVC	I
353157080525303	MW–3D[a]	1/23/2001	761.62	PVC	6.0	90	400	Open hole	B
353145080524702	MW–4S[b]	3/27/2001	802.39	PVC	4.0	23	38	0.01 slotted PVC	R
353145080524701	MW–4I B	3/26/2001	802.93	PVC	4.0	38	53	0.01 slotted PVC	R
353145080524704	MW–4I A	2/26/2002	802.39	PVC	2.0	40	55	0.01 slotted PVC	I
353145080524703	MW–4D	3/21/2001	801.84	PVC	4.0	69	400	Open hole	B
353148080524701	MW–5S	3/27/2001	786.18	PVC	4.0	10	20	0.01 slotted PVC	R
353148080524702	MW–5I	3/27/2001	785.07	PVC	4.0	20	35	0.01 slotted PVC	I
353148080524703	MW–5D	3/13/2001	784.73	PVC	6.0	40	400	Open hole	B
353151080524601	MW–6S	3/28/2001	765.32	PVC	4.0	8	18	0.01 slotted PVC	R
353151080524602	MW–6I[c]	4/2/2001	764.59	PVC	4.0	20	35	0.01 slotted PVC	I
353151080524604	MW–6I B	3/4/2002	765.73	PVC	4.0	15	30	0.01 slotted PVC	I
353151080524603	MW–6D	3/6/2001	765.84	PVC	4.0	69	400	Open hole	B
353144080524601	GEOPROBE (GP) 1	9/13/2000	805.10	PVC	0.5	29	39	0.01 slotted PVC	R
353148080524901	GEOPROBE (GP) 2	9/21/2000	793.48	PVC	0.5	27	36	0.01 slotted PVC	R
353146080524601	GEOPROBE (GP) 3	10/3/2000	791.04	PVC	0.5	22	31	0.01 slotted PVC	R
353145080524401	GEOPROBE (GP) 4	9/19/2000	793.08	PVC	0.5	25	34	0.01 slotted PVC	R
353149080524801	GEOPROBE (GP) 5	10/3/2000	786.81	PVC	0.5	23	32	0.01 slotted PVC	R
353150080524701	GEOPROBE (GP) 6	10/4/2000	776.58	PVC	0.5	16	25	0.01 slotted PVC	R
353151080524701	GEOPROBE (GP) 7	10/4/2000	767.37	PVC	0.5	9	18	0.01 slotted PVC	R
353151080524501	GEOPROBE (GP) 8	10/10/2000	768.04	PVC	0.5	8	18	0.01 slotted PVC	R
353147080524401	AUGER (WL) 1	10/10/2000	784.27	PVC	1.0	20	30	0.01 slotted PVC	R
353148080524601	AUGER (WL) 2	10/9/2000	780.74	PVC	1.0	16	26	0.01 slotted PVC	R
353150080524501	AUGER (WL) 3	10/10/2000	770.46	PVC	1.0	10	20	0.01 slotted PVC	R
353149080524401	AUGER (WL) 4	10/10/2000	775.85	PVC	1.0	17	26	0.01 slotted PVC	R
0214262175	Lake Norman	9/3/2002	762.18	na	na	na	na	na	SW

[a]Well was abandoned in March 2002.

[b]Well was drilled deeper in February 2002.

[c]Well was abandoned in February 2002.

Water-Resources Data

Borehole geophysical logs were collected from five bedrock wells at the LPRS (figs. 28–32). Data collected from these wells include caliper, natural gamma, short-normal and long-normal resistivity logs; fluid-temperature and fluid-resistivity logs; heat-pulse flowmeter data (both ambient and stressed conditions); and OTV images (figs. 28–32). Bedrock well MW–3D was abandoned early in the study, and no geophysical logs were collected.

Monthly water levels were measured in all 32 wells (including piezometers) as well as at the surface-water site at Lake Norman at the LPRS. Water levels have been measured in well cluster MW–1 since January 2001, in well clusters MW–2 and MW–3 since February 2001, and in well clusters MW–4, MW–5, and MW–6 since May 2001 (fig. 33). Periodic water levels have been recorded in the piezometers (table 3) from September 2000 through September 2004 (fig. 34). Periodic lake levels were plotted against the ground-water levels recorded in well clusters MW–3 and MW–6 (figs. 33C and 33F, respectively). Well MW–1S was dry from January 2001 through June 2003, and well MW–5S was dry from January 2001 through March 2003 and January 2004 through September 2004. Regolith well MW–4S and transition-zone well MW–6I were discontinued in February 2002. Ground-water altitudes at well cluster MW–1 ranged from about 770 to 780 ft in the shallow and transition zones and about 762 to 770 ft in the bedrock zone. Ground-water altitudes at well cluster MW–2 ranged from about 777 to 788 ft in the shallow and transition zones and about 774 to 786 ft in the bedrock zone. Ground-water altitudes at well cluster MW–3 ranged from about 752 to 758 ft in all three zones. Ground-water altitudes at well cluster MW–4 ranged from about 765 to 775 ft in the shallow and transition zones and about 753 to 760 ft in the bedrock zone. Ground-water altitudes at well cluster MW–5 ranged from about 760 to 768 ft in the shallow and transition zones and about 752 to 760 ft in the bedrock zone. Ground-water altitudes at well cluster MW–6 ranged from about 752 to 758 ft in the shallow and transition zones and about 753 to 760 ft in the bedrock zone. The water-level altitudes in the bedrock zone were consistently lower than water-level altitudes in the shallow and transition zones at well clusters MW–1, MW–2, MW–4, and MW–5 (fig. 33). The water-level altitudes in the bedrock zone were consistently higher than water-level altitudes in the shallow and transition zones at well cluster MW–6 (fig. 33). Ground-water altitudes in the piezometers ranged from about 753 to 777 ft (fig. 34). Detailed summaries of ground-water-level data recorded in the LPRS wells for water years 2001–04 are published in USGS annual data reports for North Carolina (Howe and others, 2002, 2003, 2004, and 2005).

Ground-water levels were recorded hourly in three wells in cluster MW–2 from March 2001 to September 2004 (fig. 35). Ground-water levels in bedrock well MW–2D decreased substantially in November 2002 likely as a result of the pumping of nearby water-supply wells and an imprint pattern under the seasonal fluctuations observed in the cluster MW–2 wells.

Ground-water altitude maps were constructed for the two water-level extremes for the LPRS for the study period of October 18, 2002, to September 23, 2003 (fig. 36). Maximum and minimum water levels measured in the shallow regolith wells, and a grid of piezometers were used to construct these ground-water altitude maps for the shallow system.

Slug tests were conducted in eight wells at the LPRS in May 2002 and November 2003. A 5-ft long, 3.5-inch diameter PVC bailer was used to displace water in the wells. The slug tests were conducted to estimate hydraulic conductivity in the three aquifer zones tapped by the wells—the shallow regolith, transition zone, and bedrock. The wells and intervals tested and the hydraulic conductivity values are given in table 4.

Table 4. Analytical results of slug tests in wells at the Langtree Peninsula research station, North Carolina.

Well number	Screened/Open interval (feet below land surface)	Hydraulic conductivity (feet per day)
Regolith wells		
MW–2S	13–28	5
MW–3S	5–15	2
MW–6S	8–18	3
Transition-zone wells		
MW–1I	38–53	0.6
MW–3I	43–73	2
Bedrock wells		
MW–2D	53–400	0.4
MW–5D	40–400	7
MW–6D	69–400	2

Two sets of water-quality samples were collected from most of the wells (excluding the piezometers) and at 2-ft (top sample) and 12-ft (bottom sample) depths in Lake Norman, once in August 2002 and again in March 2003. Wells MW–1S and MW–5S were not sampled because of low water levels (dry), and only one transition-zone well (MW–4I) was sampled at well cluster MW–4. Results of the water-quality data collected are depicted in Piper diagrams (fig. 37) for all sampling dates and in Stiff diagrams (fig. 38) for March 2003. Major ion geochemistry in periodic ground-water samples from the shallow regolith and transition zone and in the lake samples is shown in figure 37A, and major ion geochemistry in ground-water samples from the open-hole bedrock wells at the LPRS is shown in figure 37B. Major ion geochemistry in ground-water-quality samples collected in March 2003 is

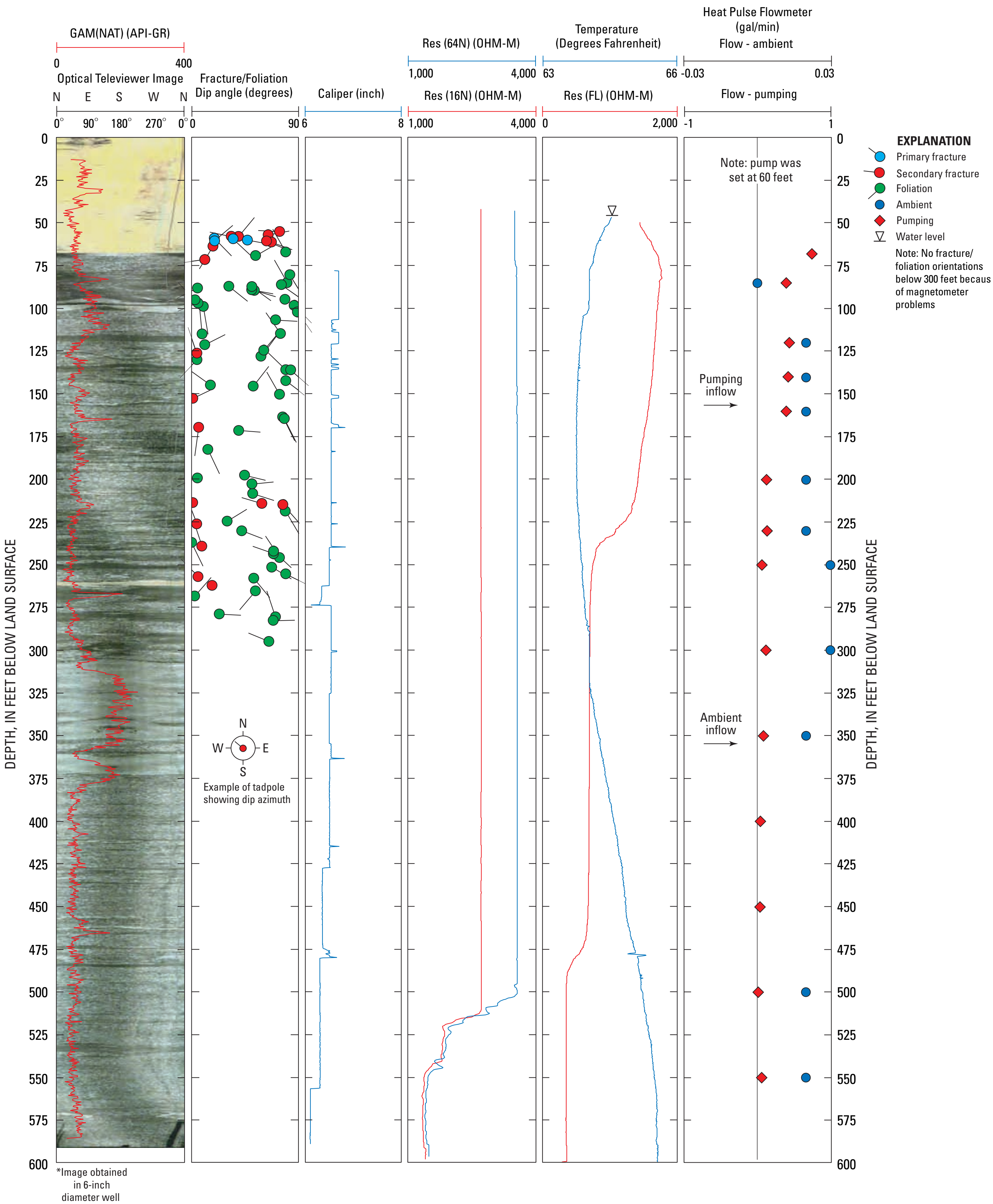

Figure 28. Geophysical logs of bedrock well MW–1D at the Langtree Peninsula research station, North Carolina.

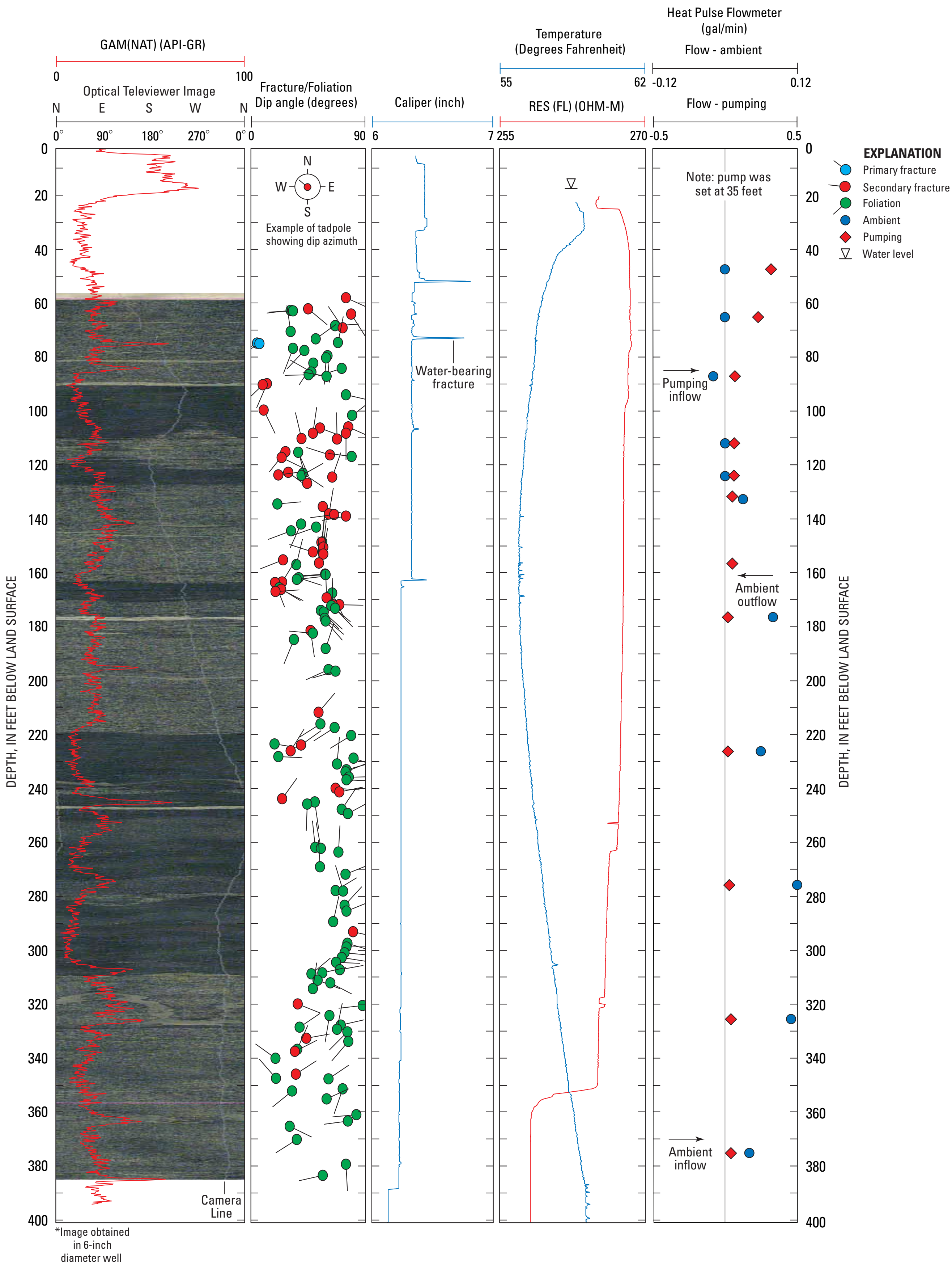

Figure 29. Geophysical logs of bedrock well MW–2D at the Langtree Peninsula research station, North Carolina.

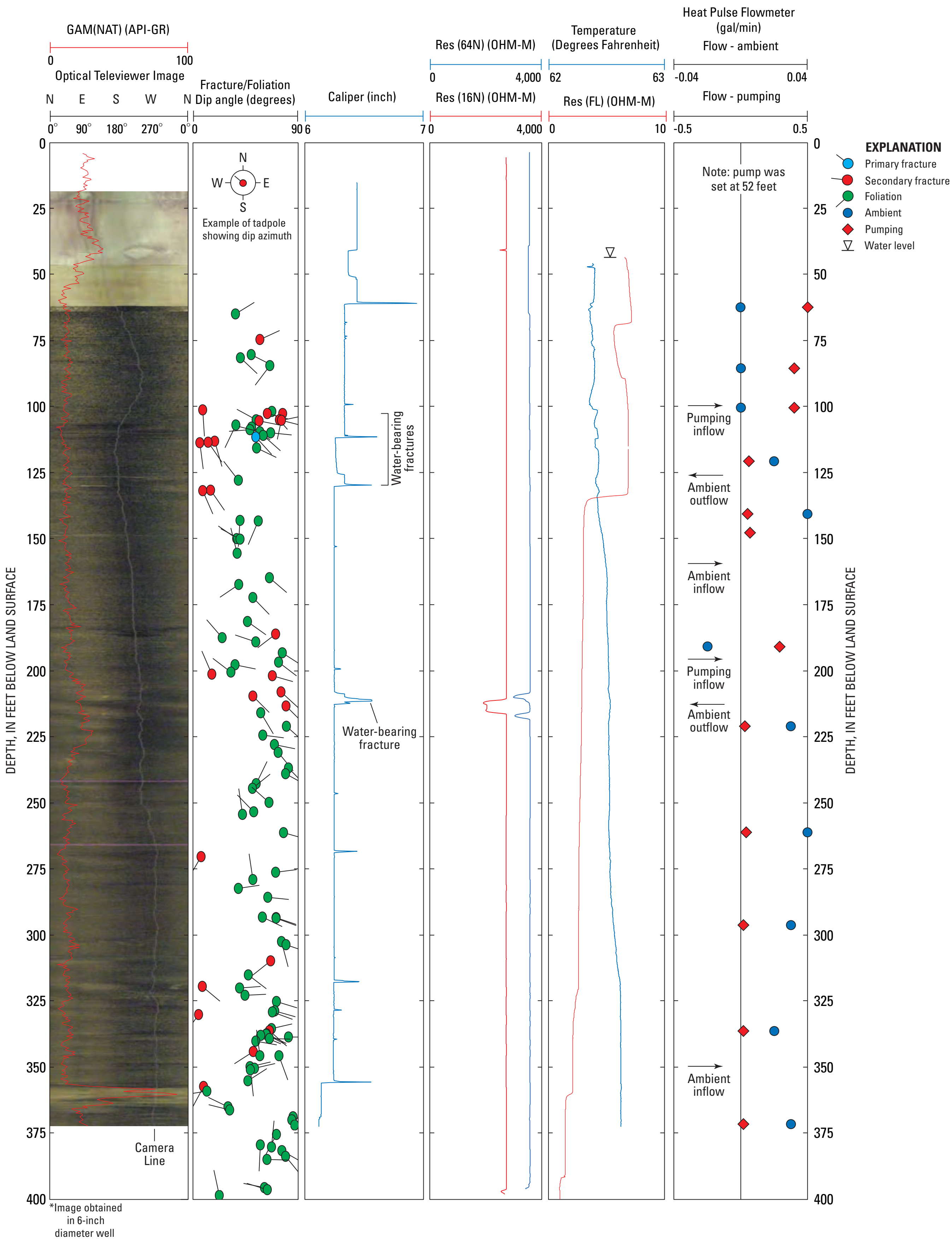

Figure 30. Geophysical logs of bedrock well MW–4D at the Langtree Peninsula research station, North Carolina.

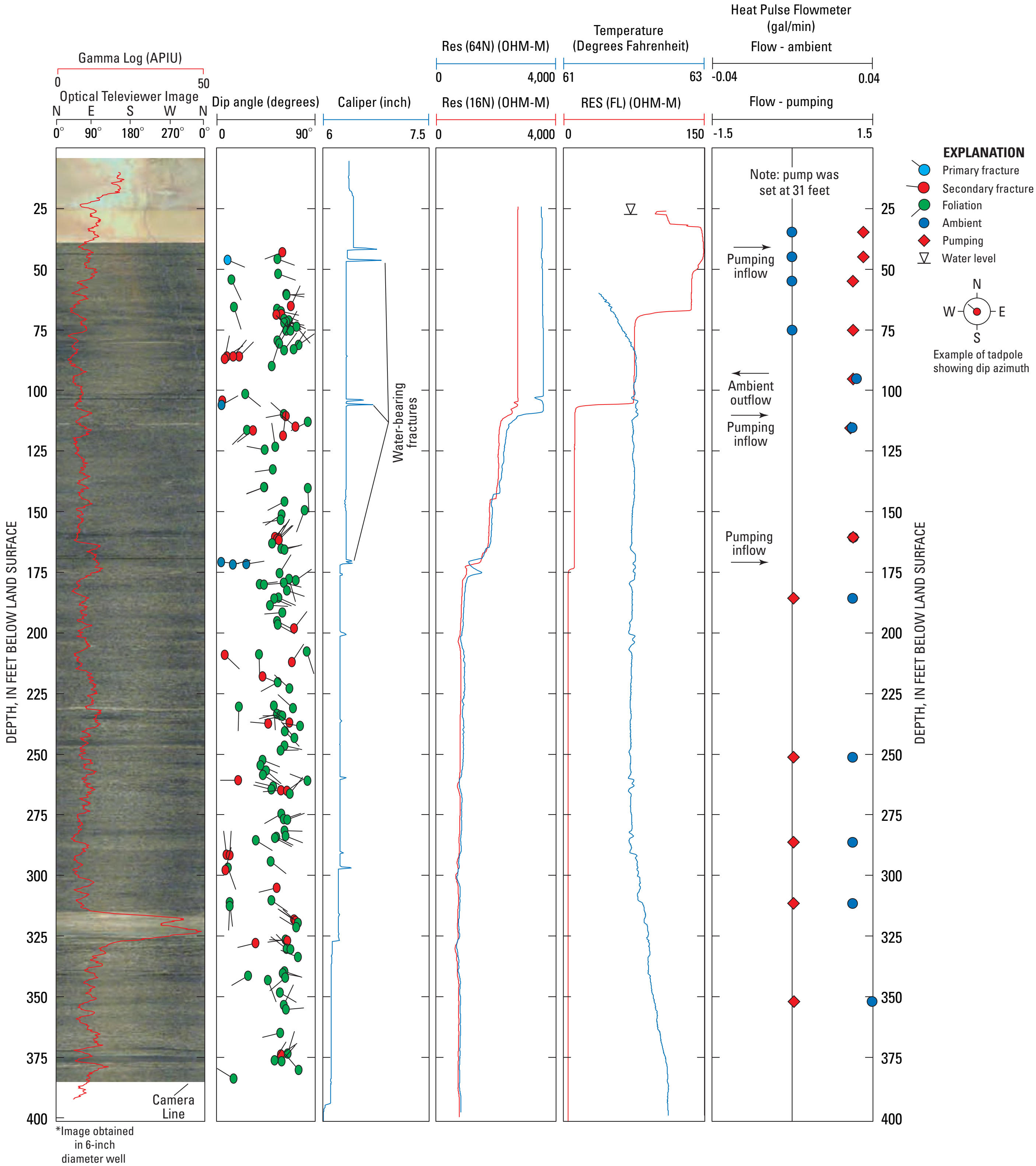

Figure 31. Geophysical logs of bedrock well MW–5D at the Langtree Peninsula research station, North Carolina.

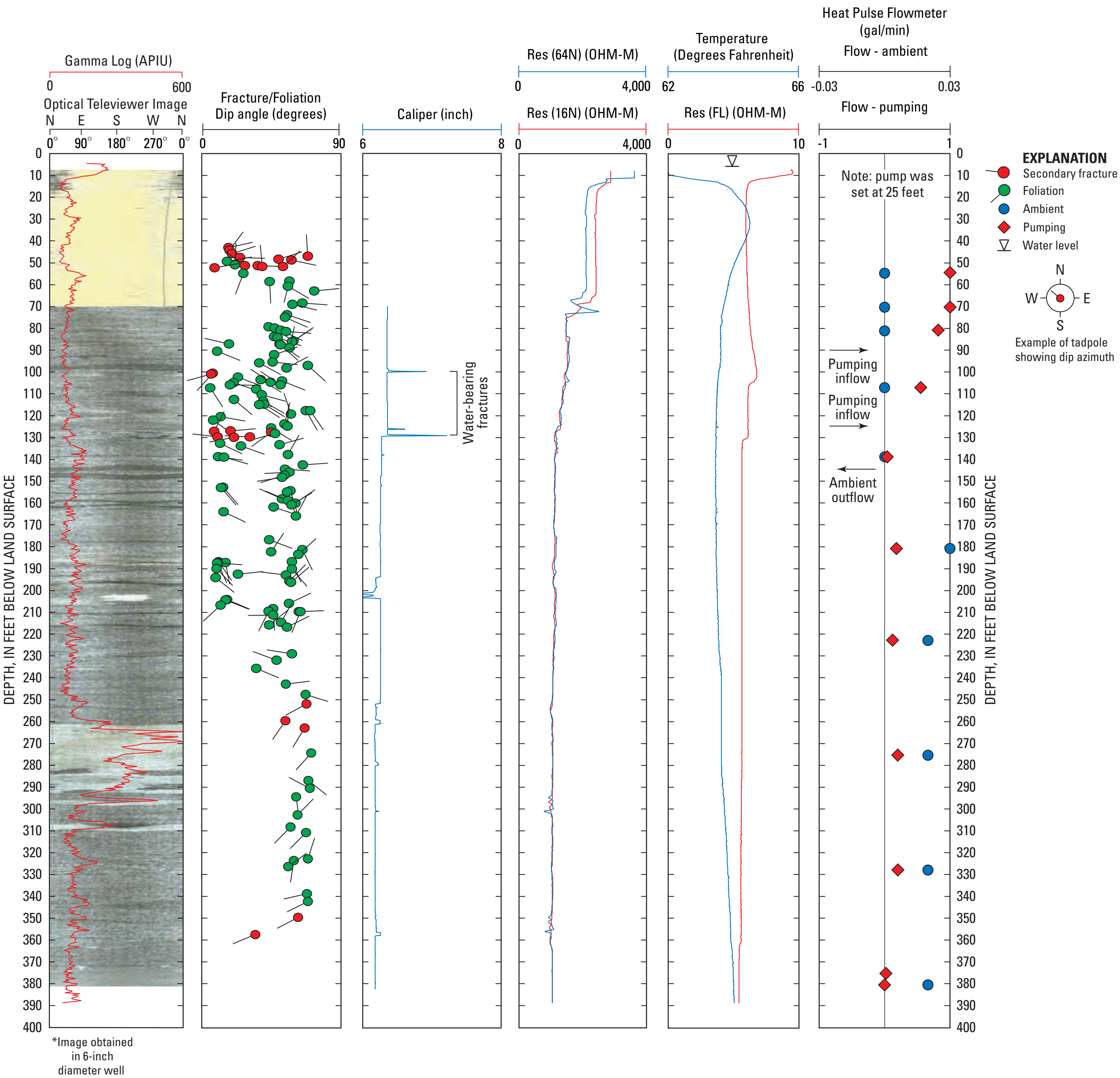

Figure 32. Geophysical logs of bedrock well MW–6D at the Langtree Peninsula research station, North Carolina.

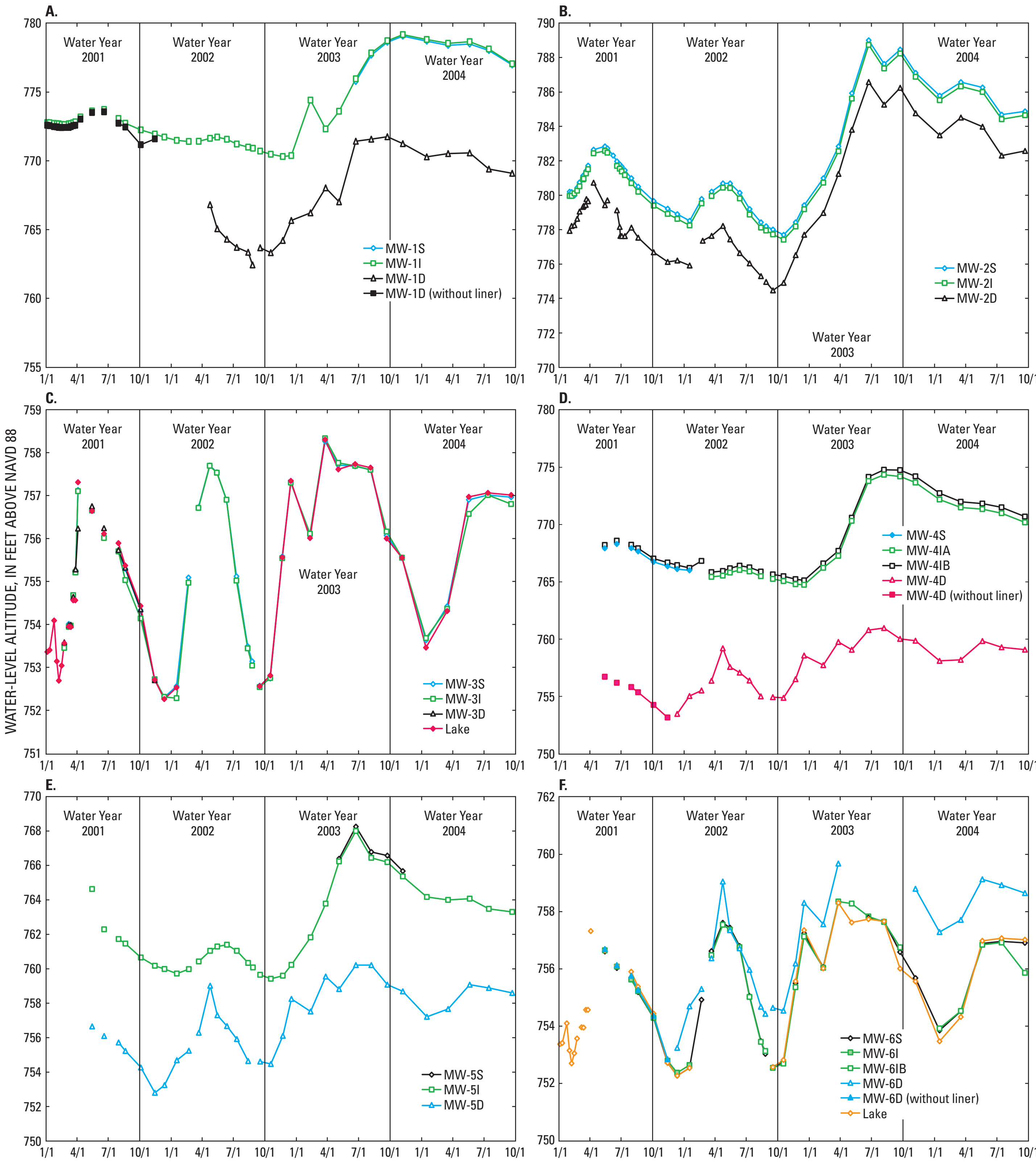

Figure 33. Periodic ground-water levels recorded in well clusters (A) MW–1, (B) MW–2, (C) MW–3, (D) MW–4, (E) MW–5, and (F) MW–6 at the Langtree Peninsula research station, North Carolina.

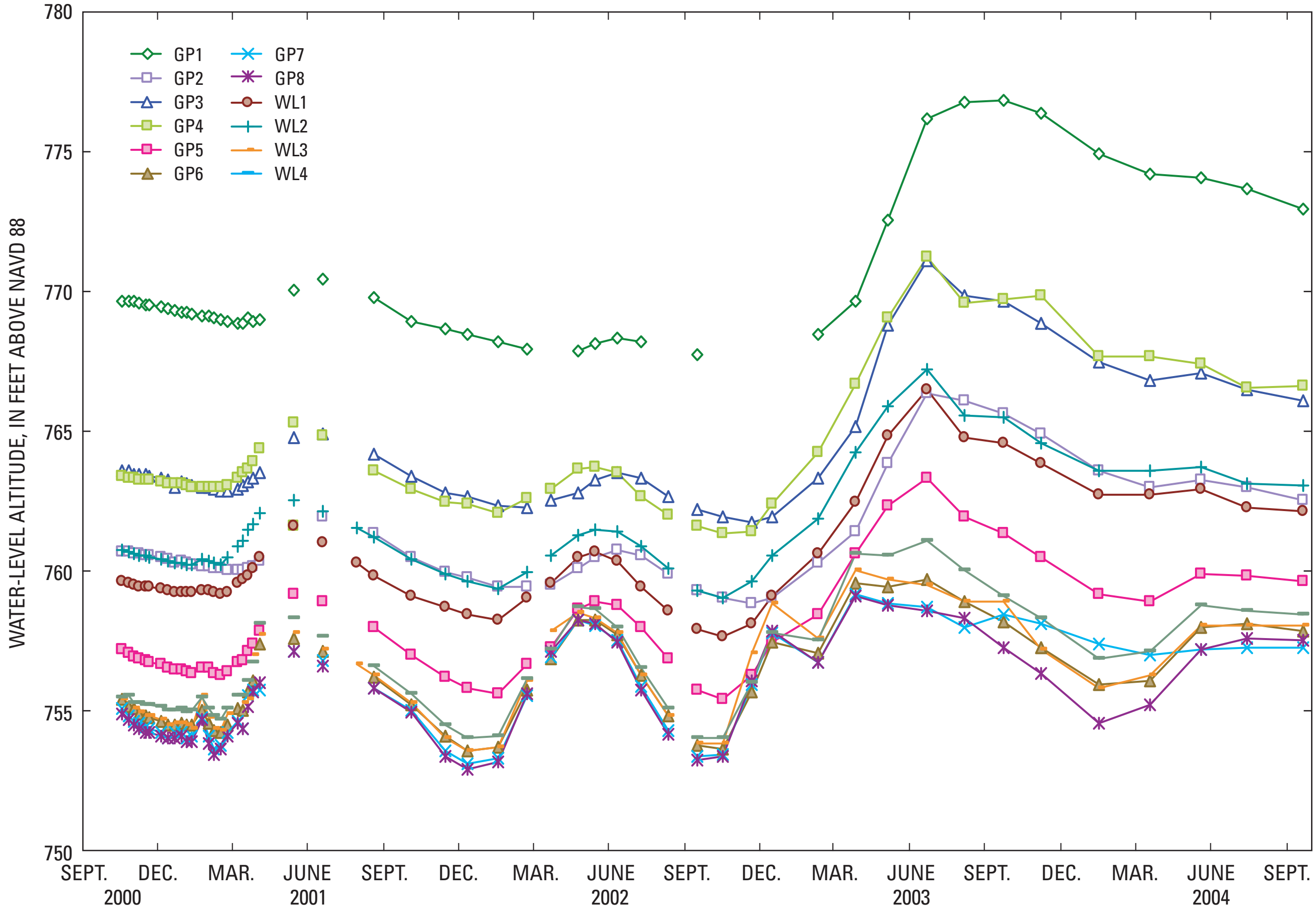

Figure 34. Periodic ground-water levels recorded in piezometers at the Langtree Peninsula research station, North Carolina (GP, geoprobe; WL, auger).

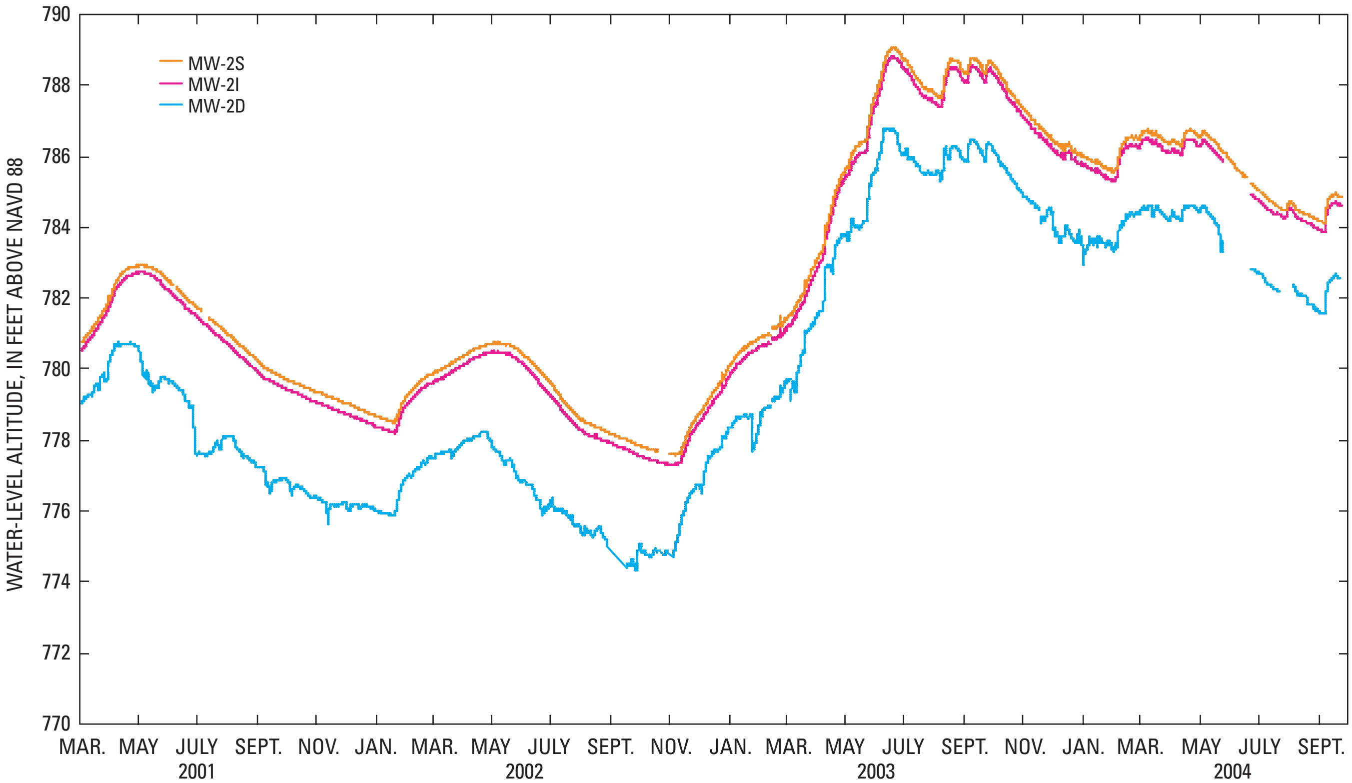

Figure 35. Continuous hourly ground-water levels recorded in well cluster MW–2 at the Langtree Peninsula research station, North Carolina.

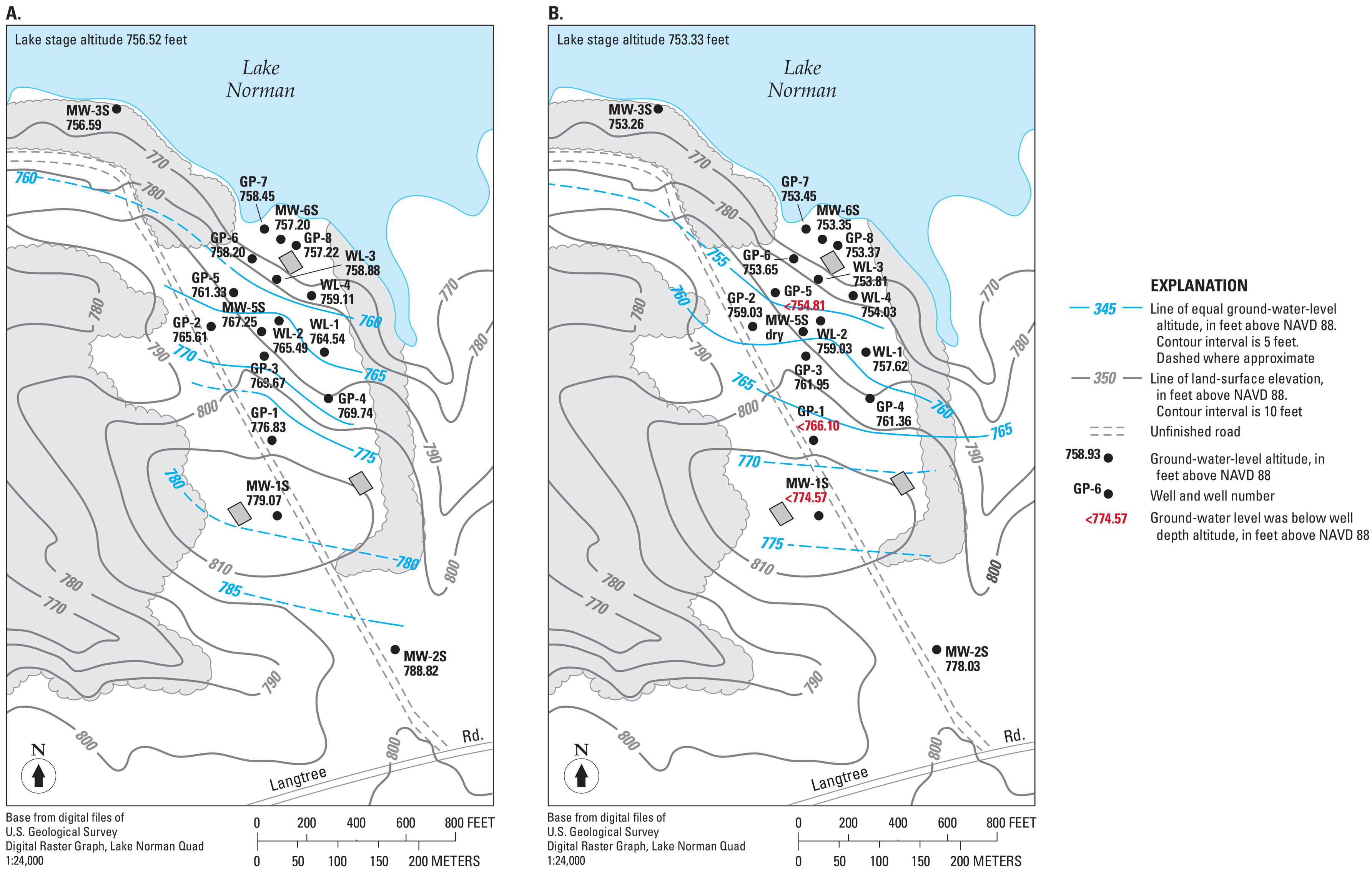

Figure 36. Water-level altitudes measured in the shallow regolith at the Langtree Peninsula research station, North Carolina, for (A) September 23, 2003 (maximum), and (B) October 18, 2002 (minimum).

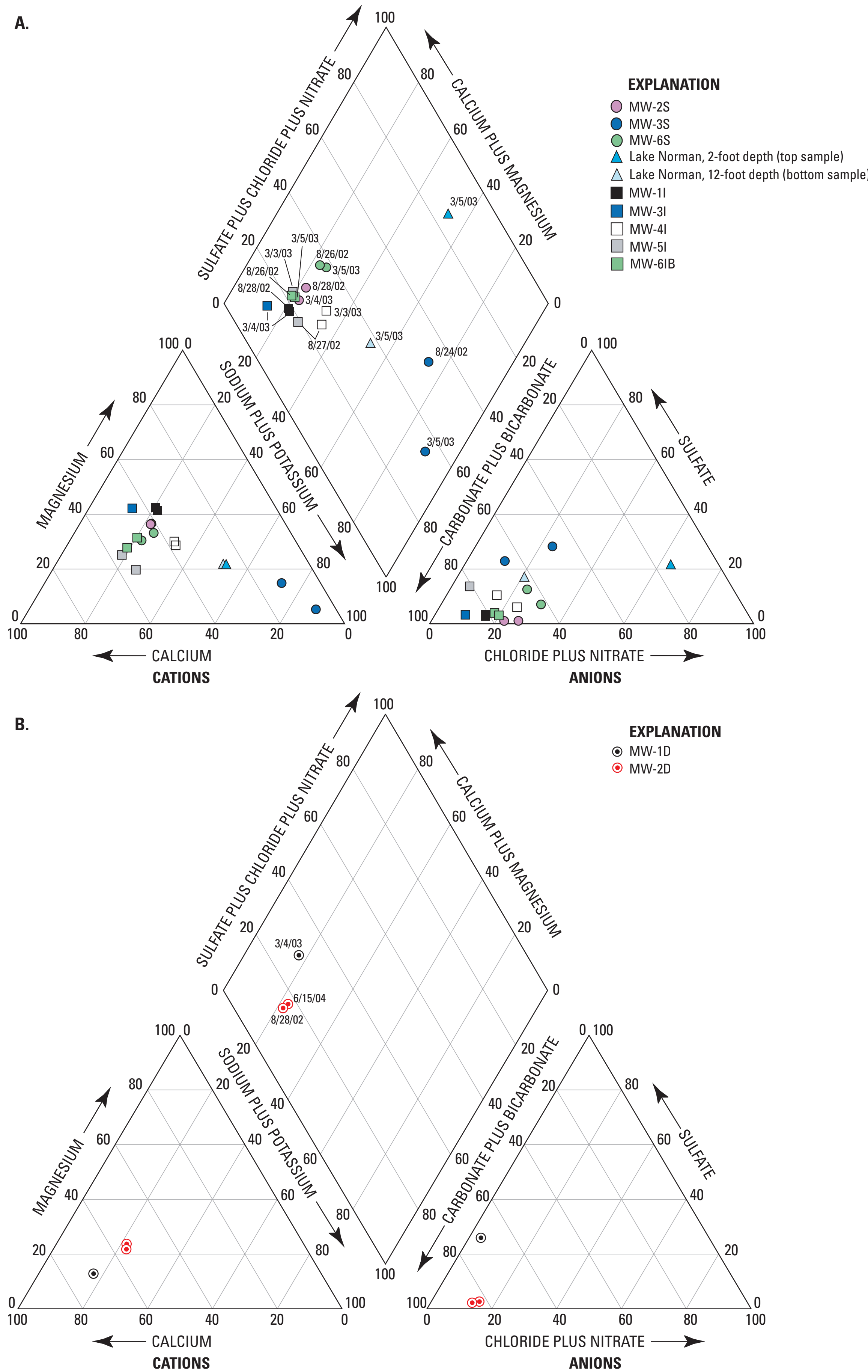

Figure 37. The water chemistry of samples from (A) regolith and transition-zone wells and the lake site, and (B) open-borehole bedrock wells at the Langtree Peninsula research station, North Carolina.

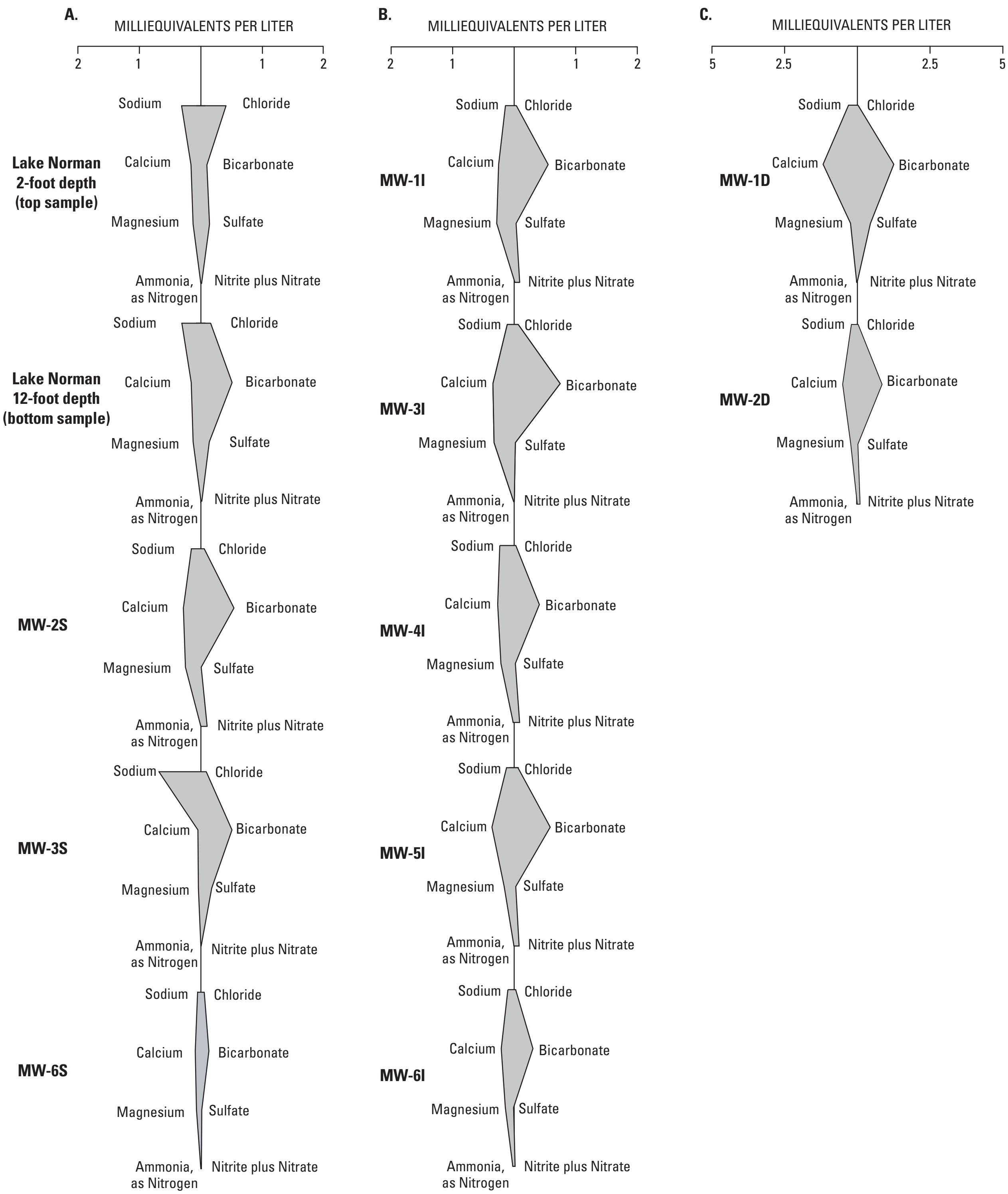

Figure 38. Major ion milliequivalents in water samples collected from (A) regolith wells and the lake site, (B) transition-zone wells, and (C) open-borehole bedrock wells at the Langtree Peninsula research station, North Carolina, March 2003.

shown in figure 38. Ranges of water-quality-data results for all sampling dates are displayed in box plots (figs. 39–41).

Water-quality data (temperature, pH, SC, and DO concentrations) were collected at hourly intervals in two zones in well cluster MW–2 at the LPRS. Hourly data were collected in MW–2S (shallow regolith) from August 2002 to July 2003 (fig. 42) and in MW–2D (bedrock) from August 2002 to March 2004 (fig. 43). Water temperature at well cluster MW–2 ranged from about 16.2 to 16.8 °C in the shallow zone and from about 16 to 16.1 °C in the bedrock zone. Specific conductance ranged from about 30 to 80 µS/cm in the shallow zone and from about 85 to 95 µS/cm in the bedrock zone. The pH ranged from about 5.6 to 6.3 in the shallow zone and from about 6.5 to 7.5 in the bedrock zone. Dissolved-oxygen concentrations ranged from about 5.7 to 7.4 mg/L in the shallow zone and from about 5 to 6 mg/L in the bedrock zone.

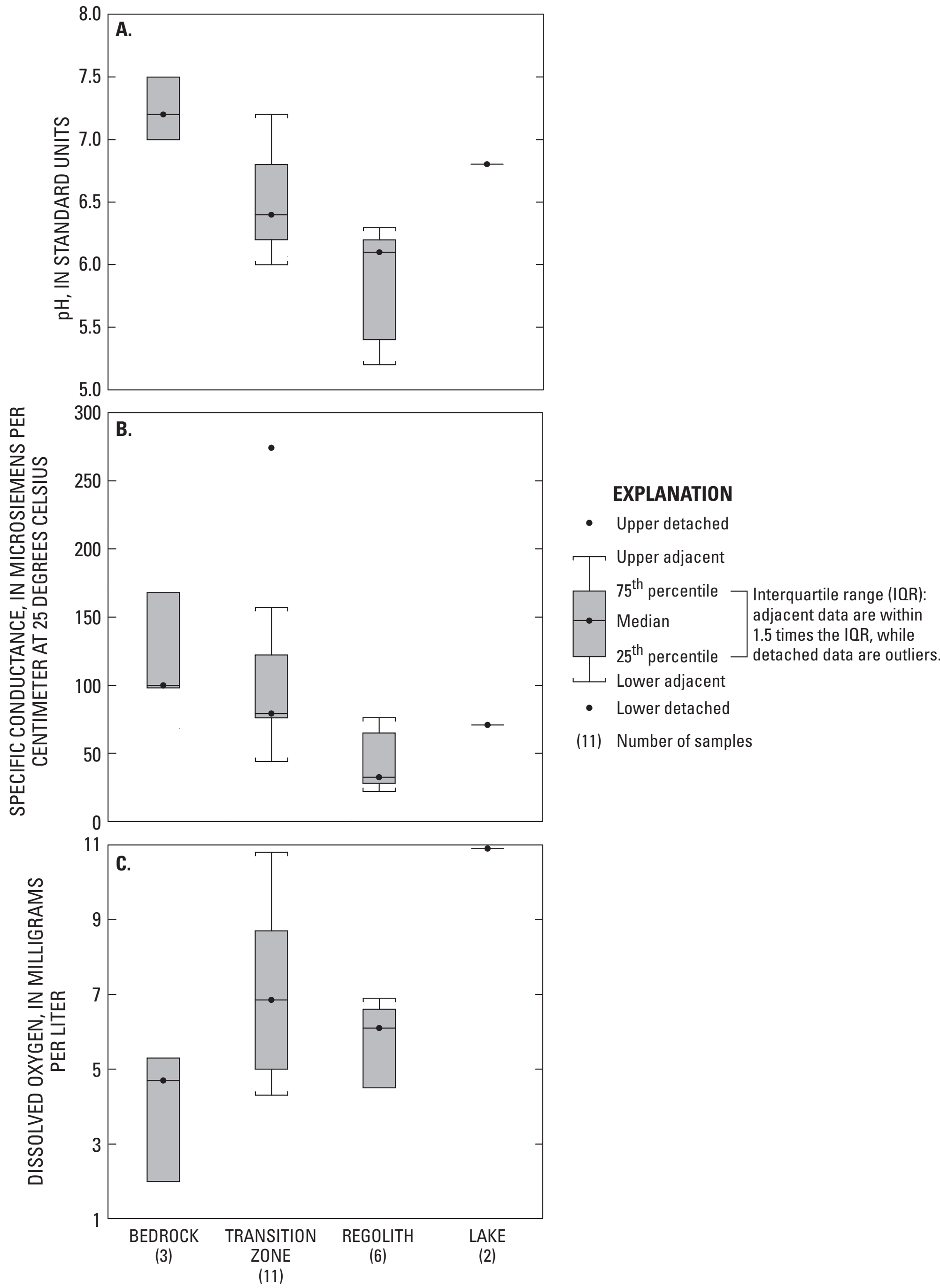

Figure 39. The range, median, and quartile statistical values for (A) pH, (B) specific conductance, and (C) dissolved oxygen for wells and the lake site during periodic sampling events at the Langtree Peninsula research station, North Carolina.

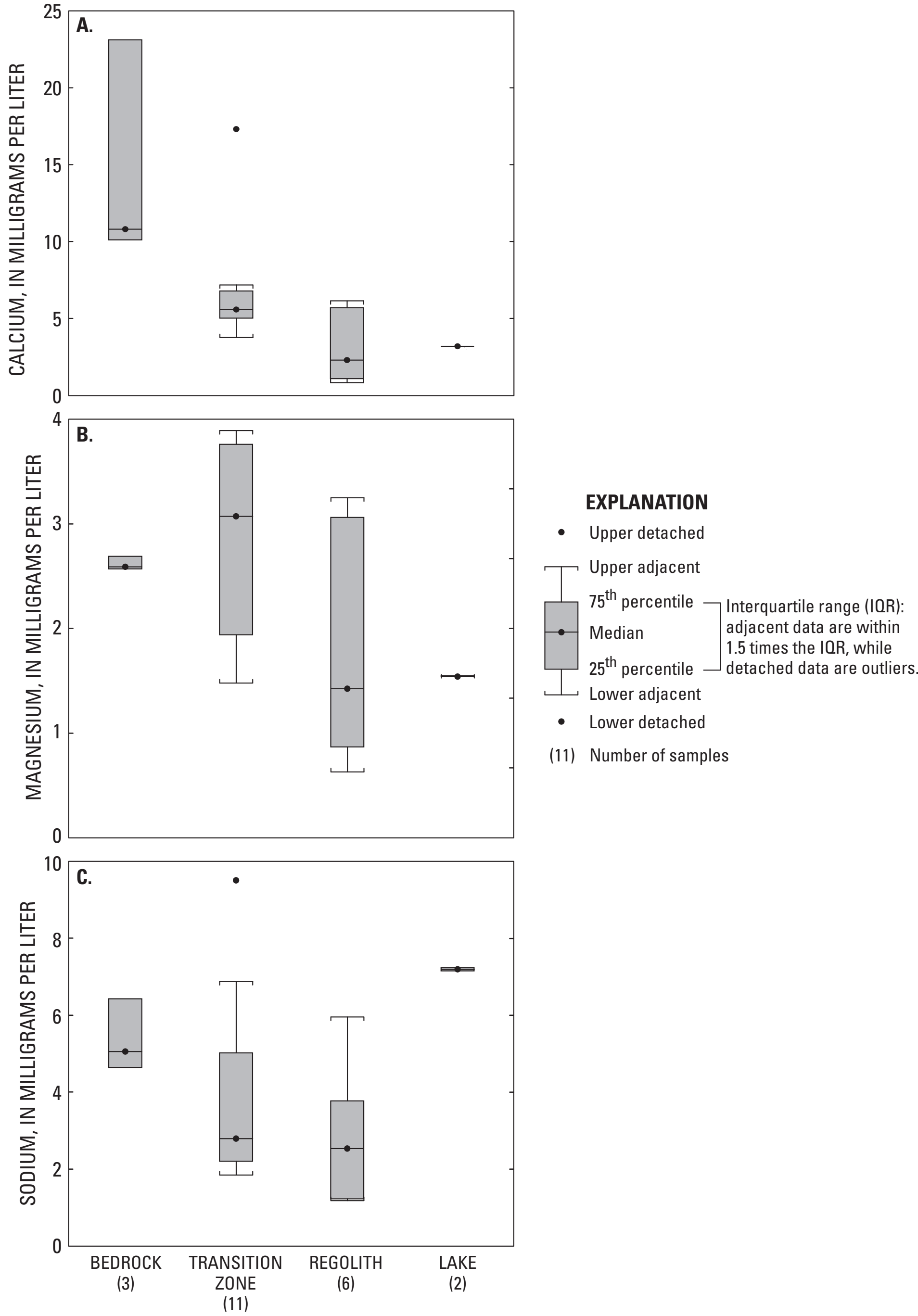

Figure 40. The range, median, and quartile statistical values for (A) calcium, (B) magnesium, and (C) sodium for wells and the lake site during periodic sampling events at the Langtree Peninsula research station, North Carolina.

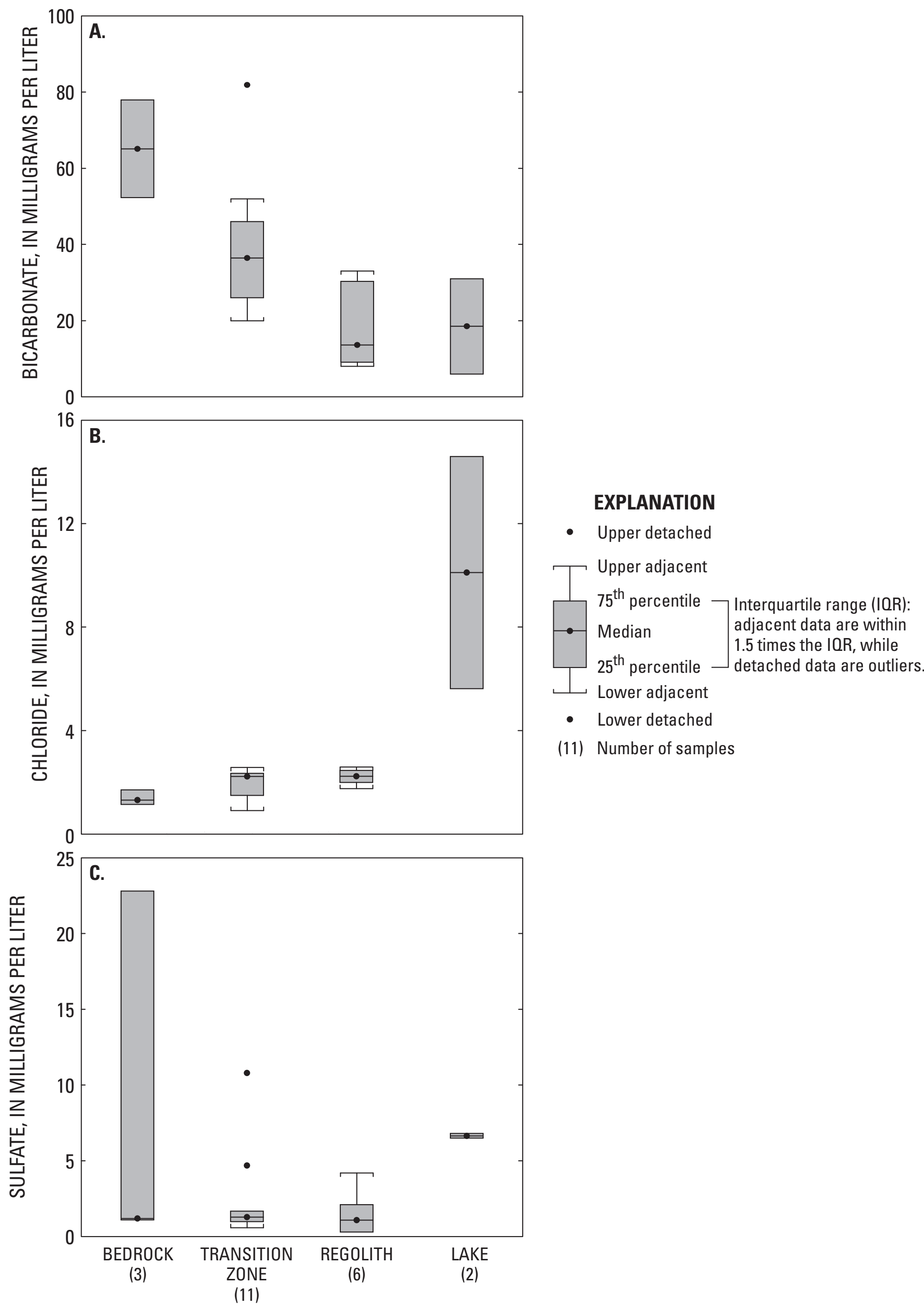

Figure 41. The range, median, and quartile statistical values for (A) bicarbonate, (B) chloride, and (C) sulfate for wells and the lake site during periodic sampling events at the Langtree Peninsula research station, North Carolina.

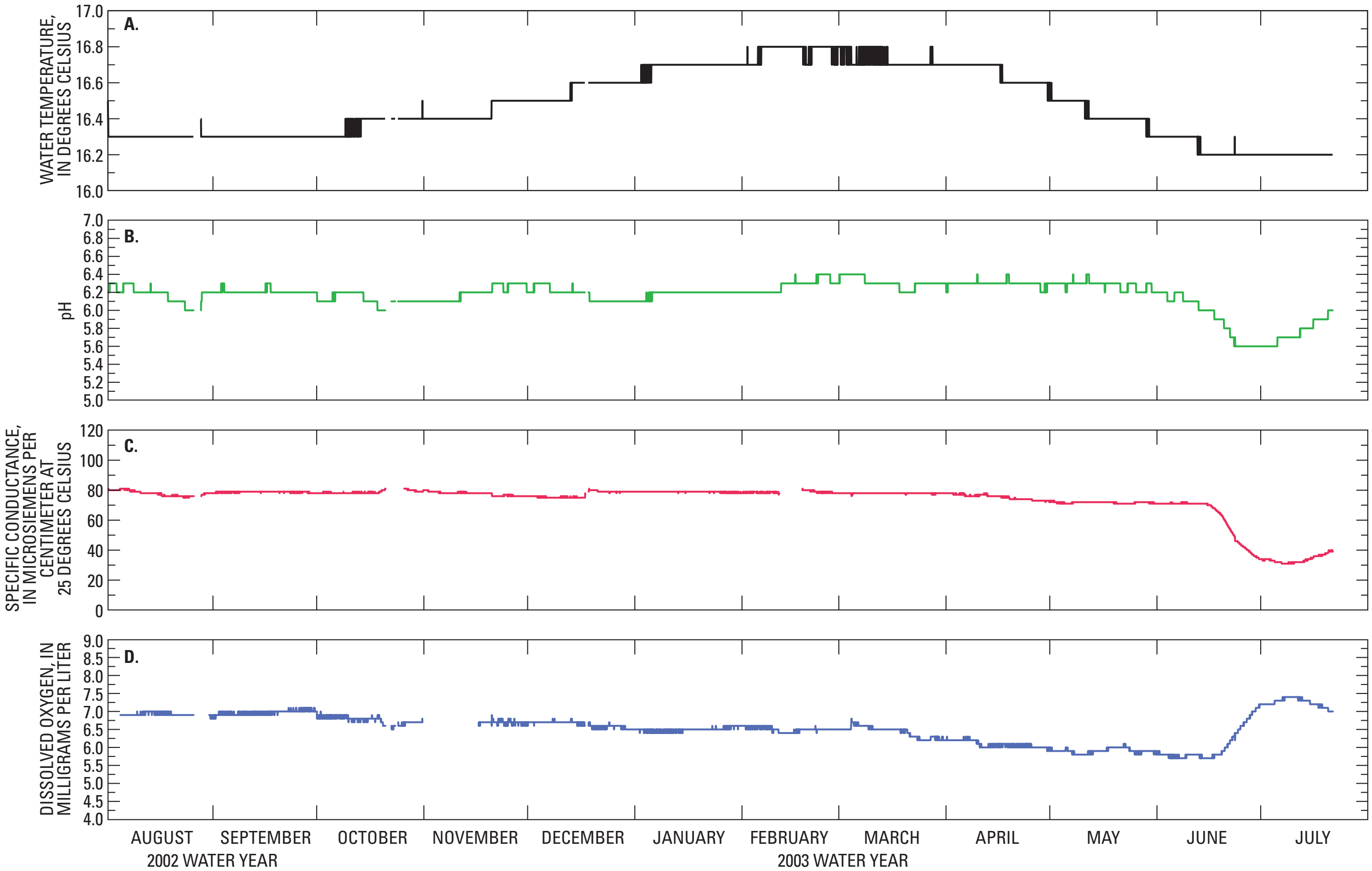

Figure 42. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–2S in the shallow regolith at the Langtree Peninsula research station, North Carolina.

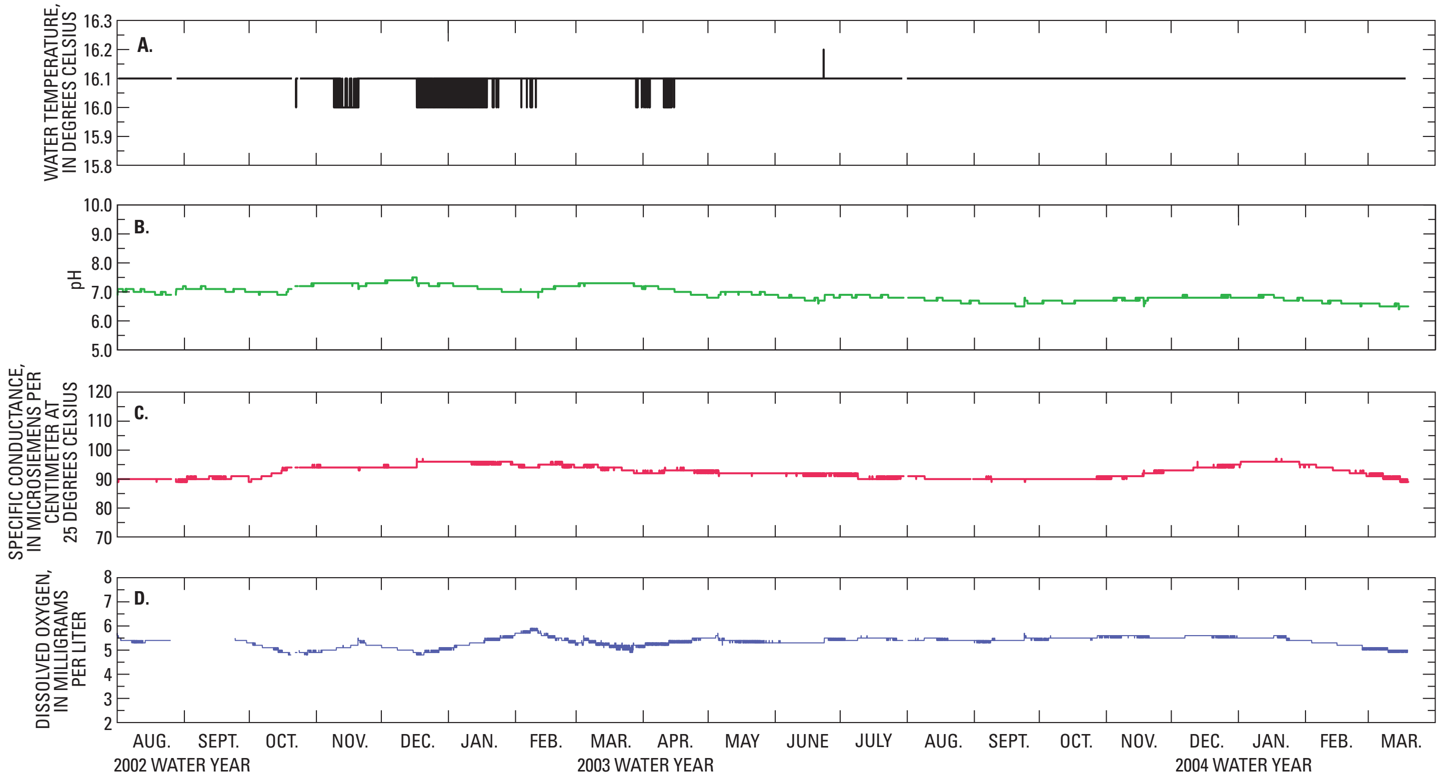

Figure 43. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–2D in bedrock at the Langtree Peninsula research station, North Carolina.

Upper Piedmont Research Station

Site Description and Geology

The Upper Piedmont research station in Rockingham County is the first hydrogeologic research station installed in the DWQ Winston-Salem Region of North Carolina as part of the PMREP (fig. 44). The UPRS is an agricultural research farm owned and operated by North Carolina State University and the North Carolina Department of Agriculture. The research station is adjacent to a 4–H educational center, and together the properties form an approximately 850-acre tract of State-owned land. The hydrogeologic research station occupies parts of both properties (figs. 45, 46). The study area, which is in the upper Wolf Island Creek watershed, encompasses approximately 150 acres about 2 miles northwest of the center of Reidsville, NC.

The UPRS lies in the Milton litho-tectonic belt in the western Piedmont Physiographic Province (fig. 44). The Milton Belt consists of heterogeneous gneisses and schists of metasedimentary and metaigneous origin. The geology of the study area consists of gently to moderately dipping amphibolite and interlayered felsic gneiss and amphibolite rock types. Regionally, the UPRS is located within the felsic gneiss (GNF) and mafic gneiss (GNM) hydrogeologic units (fig. 44). Felsic gneisses represent about 20 to 30 percent of the hydrogeologic settings in the Piedmont and Blue Ridge Provinces of North Carolina, whereas mafic gneisses represent about 18 percent (Daniel and Dahlen, 2002). The UPRS consists of two well-cluster transects, the northern (A–A') and southern (B–B'). Based on detailed geologic mapping by Horton and Geddes (in press) and geologic coring, the northern transect well clusters are located in areas of interlayered mica gneiss and schist, felsic gneiss, amphibolite, and mylonitic mica schist and gneiss; the southern transect well clusters are located in areas of felsic gneiss and amphibolite. Work that was conducted from March 2002 to September 2004 at the UPRS included the detailed geologic mapping and structural analysis of the upper Wolf Island Creek drainage basin (Horton and Geddes, in press), collection and logging of nine soil and rock cores totaling 1,100 ft of sample, installation of 19 observation wells grouped into seven clusters aligned along two transects, installation of 14 piezometers for water-level and aquifer-test monitoring, installation of a real-time DCP for monitoring of water levels and water quality in a three-well cluster and in adjacent Wolf Island Creek, monthly collection of water levels, sampling of wells, a 48-hour aquifer test, slug tests, and borehole geophysical logs.

An interesting aspect of the UPRS is the local ground-water-flow system. The well transects were located to test the hypothesis of the control of the local geology (rock structure) on ground-water flow. The geologic structure dips consistently to the south and southeast across the study area. Land surface in the northern part of the study area slopes steeply toward the north (opposite the dip direction (cut slope)), while land surface in the southern part slopes gently toward the south (in the same direction as dip (dip slope)), permitting a comparison of dip-slope to cut-slope hydrogeologic settings. One transect of well clusters was installed down each slope (dip slope and cut slope) with the intent of studying differences in ground-water flow between the two transects (figs. 47, 48). The conceptual model of the site includes a relatively short flow path down the dip slope and a relatively longer (or torturous) flow path down the cut slope.

Well Construction

Seven ground-water monitoring-well clusters that include two to four wells each as well as 14 piezometers were constructed (figs. 45, 46). All of the piezometers were installed near the northern transect. Well-cluster locations were selected to obtain water-quality and water-level data along two transects encompassing areas of recharge and discharge based on conceptual models developed for the slope-aquifer system (LeGrand and Nelson, 2004). Criteria for well locations included topographic setting, accessibility, and site boundaries. During this study, a total of 33 wells (including piezometers) were installed at the UPRS (table 5). Cross section A–A' was constructed along the northern transect from well cluster MW–N1 generally south along the cut slope to well cluster MW–N4 (fig. 47), and cross section B–B' was constructed along the southern transect from well cluster MW–S1 generally southeast along the dip slope to well cluster MW–S4 (fig. 48). Well clusters MW–N4 and MW–S1 are located in conceptual recharge areas, and well clusters MW–N1 and MW–S4 are located in discharge areas near streams. The 14 piezometers were installed to provide data during aquifer tests and for hydrogeologic site characterization. Six of the piezometers were installed in clusters of two (three clusters), each containing a shallow and transition-zone piezometer.

Each well cluster at the UPRS consists of two to four wells—a shallow water-level well to monitor ground-water conditions in the regolith, a transition zone well to monitor conditions in the partially weathered bedrock and open fractures near the top of bedrock, and a deeper bedrock well to monitor ground water in the fractured bedrock aquifer (figs. 47, 48). Well-construction information is provided in table 5. Well cluster MW–S3 contains an additional transition-zone well. Well clusters MW–N4, MW–N3, and MW–S1 do not contain regolith wells. Well clusters MW–N2, MW–N4, and MW–S4 (figs. 47, 48) each contain a well completed in the transition zone to monitor conditions in the partially weathered bedrock and open fractures in the upper part of the bedrock.

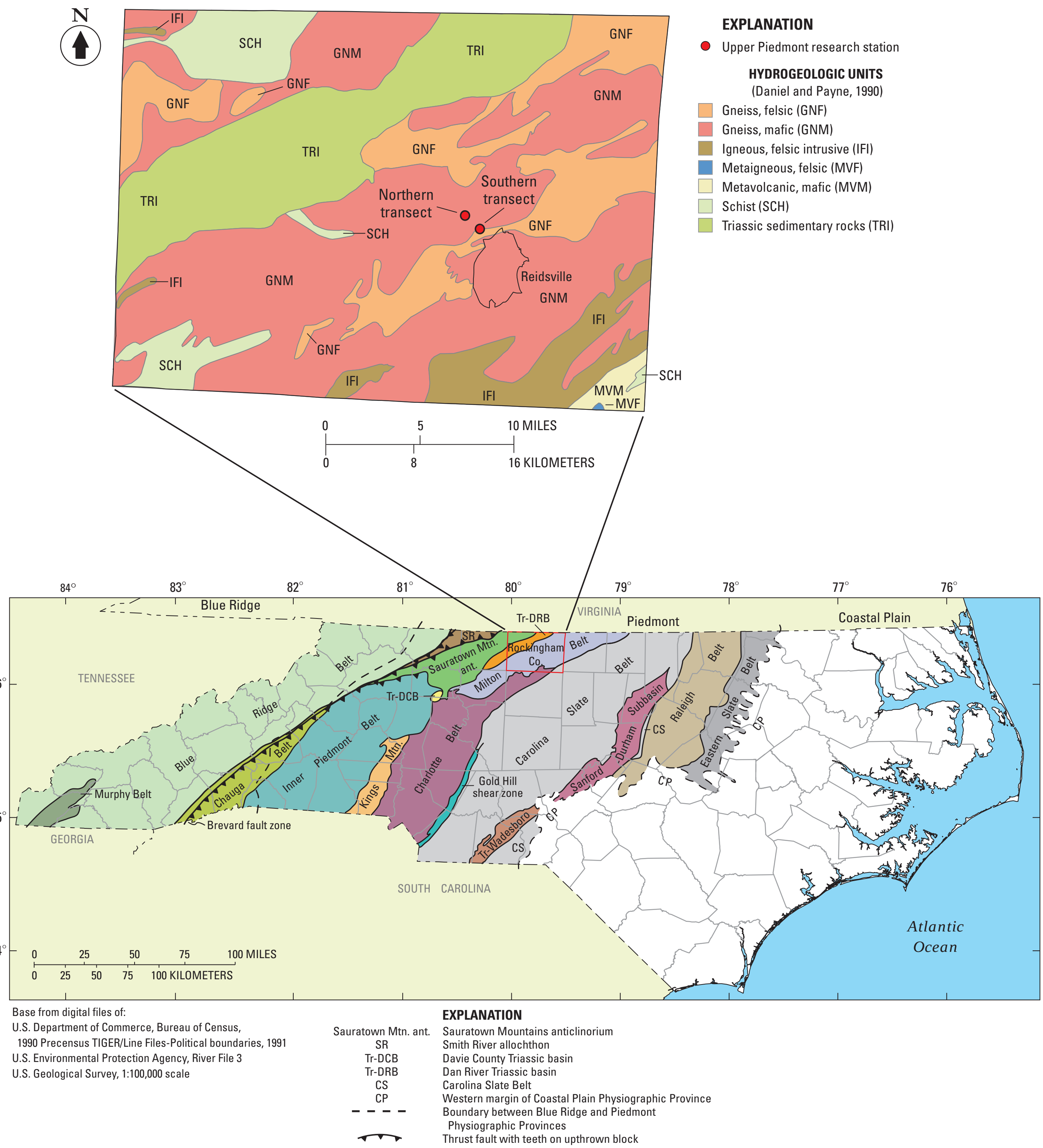

Figure 44. Locations of Upper Piedmont research station, hydrogeologic units in Rockingham County, and geologic belts delineated in North Carolina (modified from North Carolina Geological Survey, 1985; Daniel and Payne, 1990).

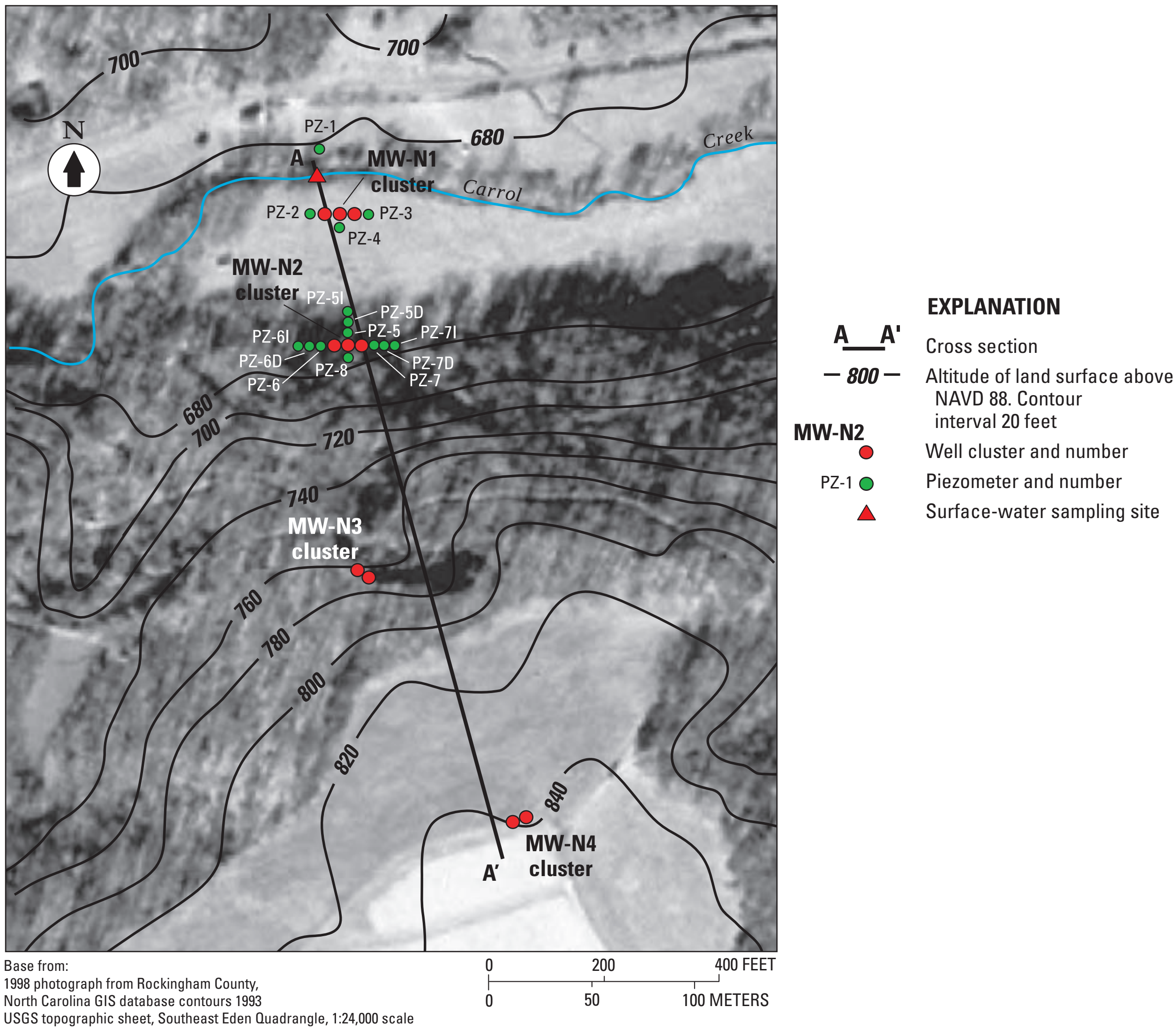

Figure 45. Aerial photograph overlaid with topographic features showing locations of well clusters, surface-water site, and line of section A–A′ along the northern transect at the Upper Piedmont research station in Rockingham County, North Carolina.

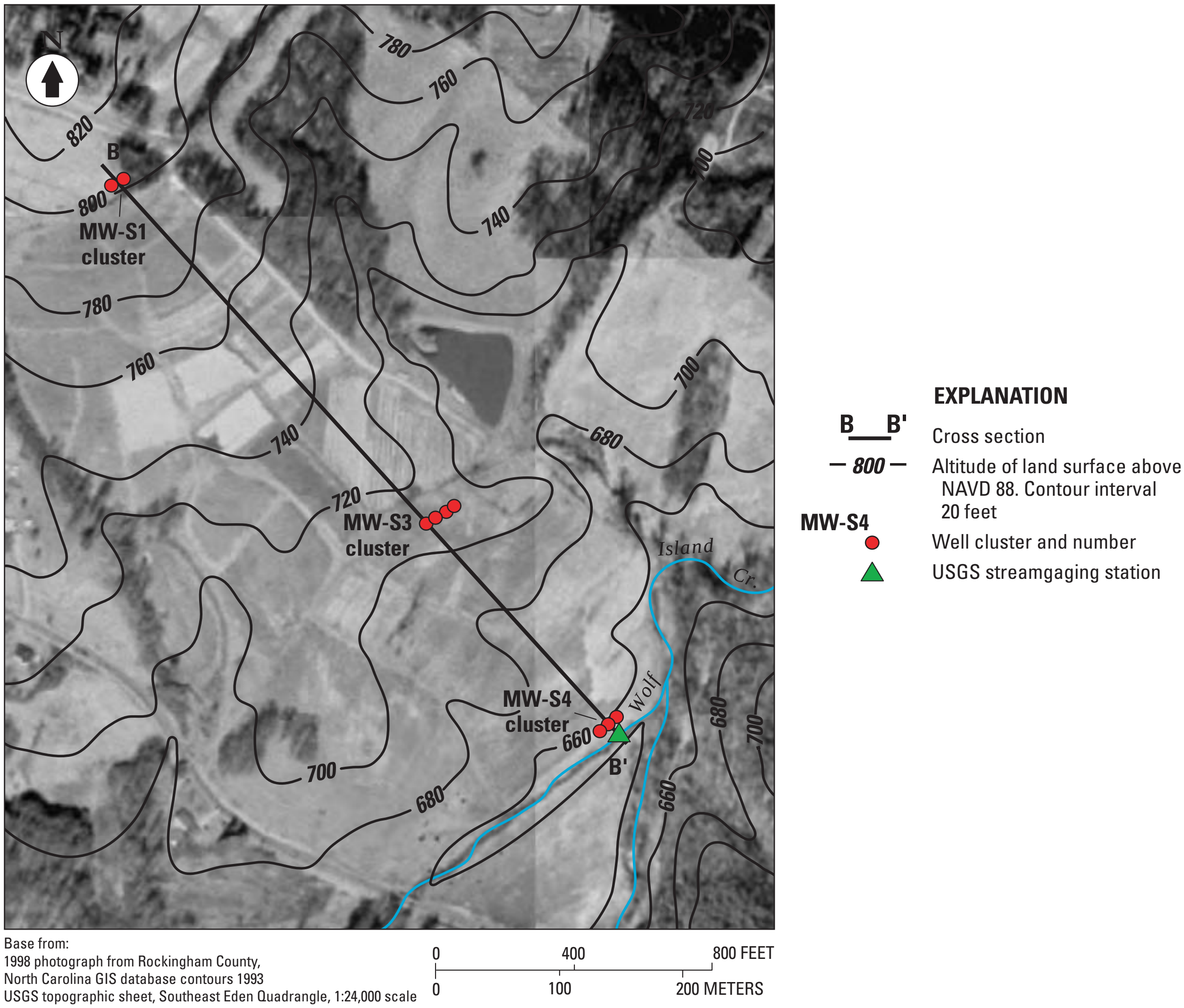

Figure 46. Aerial photograph overlaid with topographic features showing locations of well clusters, streamgaging station, and line of section B–B′ along the southern transect at the Upper Piedmont research station in Rockingham County, North Carolina.

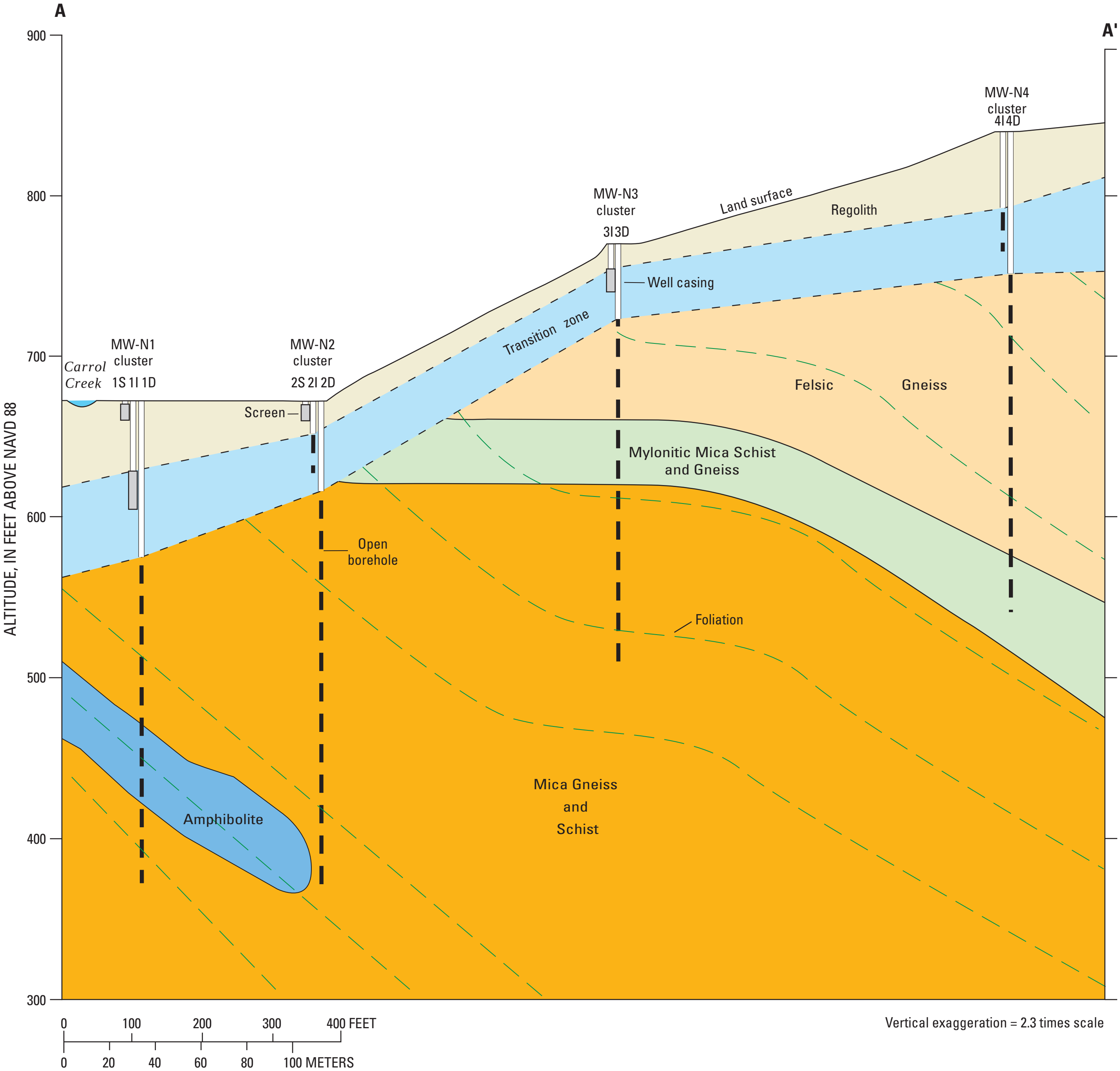

Figure 47. Generalized hydrogeologic cross section A–A' along the northern well transect at the Upper Piedmont research station, North Carolina (section location is shown in figure 45; bedrock lithologies from Horton and Geddes, in press).

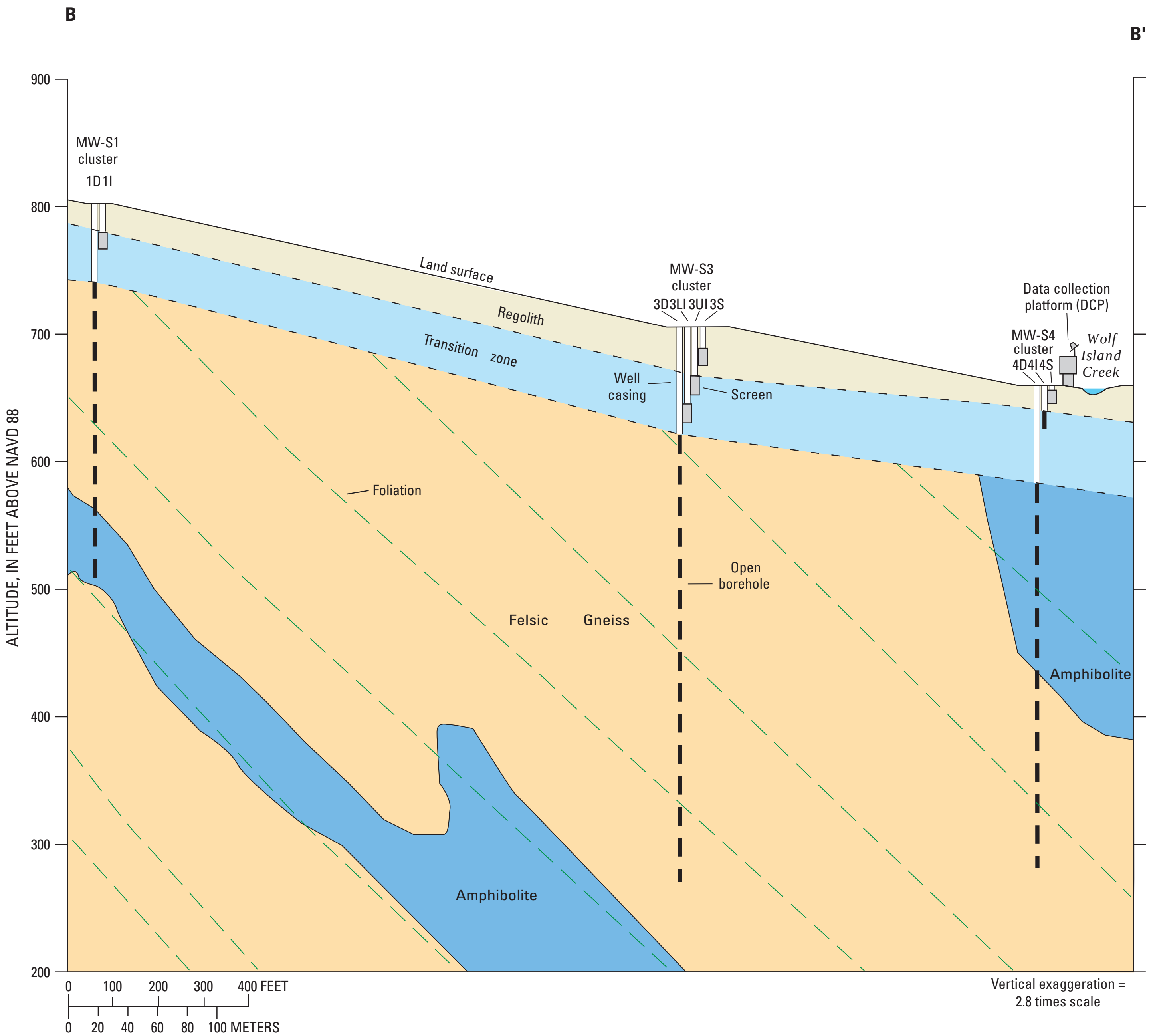

Figure 48. Generalized hydrogeologic cross section B–B′ along the southern well transect at the Upper Piedmont research station, North Carolina (section location is shown in figure 46; bedrock lithologies from Horton and Geddes, in press).

Table 5. Construction characteristics of monitoring wells and the surface-water site at the Upper Piedmont research station, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; MW, monitoring well; S, shallow; PVC, polyvinyl chloride casing; R, regolith; I or T, transition zone; D, deep; GS, galvanized steel; B, bedrock; PZ, piezometer; na, not applicable; SW, surface water]

Site identification	Station name	Construction date	Land-surface altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
						from	to		
362334079421601	MW-N1S	4/9/2002	672.76	PVC	4.0	5	15	0.01 slotted PVC	R
362334079421602	MW-N1I	5/14/2002	672.27	PVC	4.0	50	65	0.01 slotted PVC	I
362334079421603	MW-N1D	5/14/2002	672.51	GS	6.0	100	300	Open hole	B
362331079421601	MW-N2S	4/9/2002	672.48	PVC	4.0	3	13	0.01 slotted PVC	R
362331079421602	MW-N2I	5/21/2002	671.56	PVC	6.0	25	50	Open hole	T
362331079421603	MW-N2D	5/20/2002	671.91	GS	6.0	60	300	Open hole	B
362328079421701	MW-N3I	6/12/2002	770.44	PVC	4.0	15	30	0.01 slotted PVC	I
362328079421702	MW-N3D	6/12/2002	770.26	GS	6.0	40	260	Open hole	B
362323079421201	MW-N4I	5/22/2002	839.63	PVC	6.0	44	70	Open hole	T
362323079421202	MW-N4D	5/29/2002	840.19	GS	6.0	80	300	Open hole	B
362240079411801	MW-S1I	5/1/2002	803.34	PVC	4.0	35	50	0.01 slotted PVC	I
362240079411802	MW-S1D	5/1/2002	802.55	GS	6.0	61.5	301	Open hole	B
362231079410801	MW-S3S	4/10/2002	705.16	PVC	4.0	23	38	0.01 slotted PVC	R
362231079410802	MW-S3UI	4/24/2002	705.60	PVC	4.0	45	55	0.01 slotted PVC	I
362231079310803	MW-S3LI	4/23/2002	705.60	PVC	4.0	63	73	0.01 slotted PVC	I
362231079310804	MW-S3D	4/4/2002	705.48	GS	6.0	87.5	438	Open hole	B
362226079410101	MW-S4S	4/9/2002	659.50	PVC	4.0	5	15	0.01 slotted PVC	R
362226079410102	MW-S4I	3/26/2002	659.32	GS	6.0	25	35	Open hole	T
362226079410103	MW-S4D	3/25/2002	659.57	GS	6.0	77	380	Open hole	B
362335079421701	PZ-1	4/16/2003	675.95	PVC	2.0	40	50	0.01 slotted PVC	R
362334079421701	PZ-2	4/29/2003	673.02	PVC	2.0	14	24	0.01 slotted PVC	R
362334079421703	PZ-3	4/24/2003	672.17	PVC	2.0	29	39	0.01 slotted PVC	R
362334079421704	PZ-4	4/21/2003	672.25	PVC	2.0	21	31	0.01 slotted PVC	R
362332079421601	PZ-5	4/23/2003	671.62	PVC	2.0	16	26	0.01 slotted PVC	R
362332079421602	PZ-5I	8/12/2003	671.79	PVC	2.0	30	40	0.01 slotted PVC	R
362332079421603	PZ-5D	8/5/2003	671.72	PVC	2.0	70	90	0.01 slotted PVC	R
362331079421701	PZ-6	4/23/2003	672.91	PVC	2.0	8	13	0.01 slotted PVC	R
362331079421702	PZ-6I	8/13/2003	673.02	PVC	2.0	30	40	0.01 slotted PVC	R
362331079421703	PZ-6D	7/22/2003	673.04	PVC	2.0	70	90	0.01 slotted PVC	R
362332079421604	PZ-7	4/22/2003	671.43	PVC	2.0	14	19	0.01 slotted PVC	R
362331079421501	PZ-7I	8/13/2003	671.28	PVC	2.0	30	40	0.01 slotted PVC	R
362331079421502	PZ-7D	7/28/2003	671.48	PVC	2.0	75	95	0.01 slotted PVC	R
362332079421605	PZ-8	4/22/2003	672.21	PVC	2.0	14	24	0.01 slotted PVC	R
0207428225	Wolf Island Creek	12/23/2002	650	na	na	na	na	na	SW

Water-Resources Data

Borehole geophysical logs were collected from seven bedrock wells at the UPRS. Data collected from these wells include caliper, natural gamma, short-normal resistivity, and long-normal resistivity logs; fluid-temperature and fluid-resistivity logs; heat-pulse flowmeter data (both ambient and stressed conditions); and OTV images (figs. 49–55).

Monthly water levels were measured in all 33 wells at the UPRS. Water-level measurements have been recorded in well clusters MW–N1, MW–N2, MW–S1, MW–S3, and MW–S4 since May 2002, in well MW–N4 since June 2002, in well MW–N3 since August 2002 (figs. 56, 57), and in the piezometers since June 2003 (fig. 58). The period of record presented in this report is from May 2002 through September 2004. Ground-water altitudes in well cluster MW–N1 for the bedrock zone (668 to 672 ft) were consistently higher than water-level altitudes in the regolith and transition zone (665 to 667 ft). Water-level altitudes at well cluster MW–N2 in the regolith (665 to 672 ft) were consistently higher than water-level altitudes in the transition and bedrock zones (664 to 668 ft). Ground-water altitudes at well cluster MW–N3 ranged from about 742 to 746 ft in the transition zone and about 702 to 708 ft in the bedrock zone. Ground-water altitudes at well cluster MW–N4 ranged from about 802 to 815 ft in the transition zone and about 796 to 808 ft in the bedrock zone. The water-level altitudes in the transition zone were consistently higher than water-level altitudes in the bedrock zone at well clusters MW–N3 and MW–N4. Ground-water altitudes at well cluster MW–S1 ranged from about 772 to 791 ft in the transition zone and about 778 to 791 ft in the bedrock zone. Ground-water altitudes at well cluster MW–S3 ranged from about 678 to 685 ft in the regolith and transition zone and about 679 to 686 ft in the bedrock zone. Ground-water altitudes at well cluster MW–S4 ranged from about 654 to 656 ft in all three zones. The water-level altitudes in the bedrock zone were consistently higher than water-level altitudes in the regolith and transition zone at well clusters MW–S1, MW–S3, and MW–S4. The water-level altitudes for the regolith were consistently higher than water-level altitudes in the transition zone at piezometer clusters PZ–5, PZ–6, and PZ–7. Ground-water altitudes in the piezometers ranged from about 666 to 671 ft. –Detailed summaries of ground-water-level data recorded in the UPRS wells for water years 2002–04 are published in USGS annual data reports for North Carolina (Howe and others, 2003, 2004, 2005).

Continuous ground-water levels were recorded in four wells, and stage was recorded in a nearby stream (Wolf Island Creek, station 0207428225) at the UPRS. Ground-water levels were recorded hourly in all three wells in well cluster MW–S4 from May 2003 to October 2004 (fig. 59) and in bedrock well MW–S3D from November 2003 to March 2004 (fig. 60). Stage in Wolf Island Creek was recorded at 15-minute intervals from May 2003 to September 2004, and continuous stage was plotted hourly for comparison to well cluster MW–S4 (fig. 59).

Slug tests were conducted in six wells at the UPRS during September 2002. A 5-ft long, 3.5-inch diameter PVC bailer was used to displace water in the wells. The slug tests were conducted to obtain estimates of hydraulic conductivity for the three aquifer zones tapped by the wells—the regolith, transition zone, and bedrock. The estimates obtained are representative of conditions in the immediate vicinity of the tested wells. The wells and intervals tested and the hydraulic conductivity values are given in table 6.

Table 6. Analytical results of slug tests in wells at the Upper Piedmont research station, North Carolina.

Well number	Screened/Open interval (feet below land surface)	Hydraulic conductivity (feet per day)
	Regolith wells	
MW-S4S	5–15	4
	Transition-zone wells	
MW-N2I	25–50	8
MW-S3LI	63–73	3
MW-S4I	25–35	10
	Bedrock wells	
MW-N2D	60–300	0.4
MW-S3D	87.5–438	0.8

Water-quality samples were collected from all wells, with the exception of the piezometers, and from Wolf Island Creek and Carrol Creek at the UPRS (figs. 45, 46). To date (2006), water-quality samples have been collected twice—once in December 2002 and again during February through April 2004. During the second sampling event (February–April 2004) the multifunction BAT3 (Shapiro, 2001) inflatable packer system was used in the bedrock wells to isolate fracture zones. Major ion geochemistry in periodic water-quality samples from the regolith, transition zone, and in surface-water samples is shown in figure 61A; major ion geochemistry in periodic water-quality samples from the open bore-hole bedrock wells at the UPRS is shown in figure 61B. Major ion geochemistry in water-quality samples collected in December 2002 at the UPRS is shown in figure 62. Ranges in values of major ion geochemistry and physical properties are shown in box plots in figures 63–65.

Continuous real-time water-quality properties were monitored in all three ground-water zones in well cluster MW–S4 and in Wolf Island Creek. Hourly data from MW–S4S (shallow regolith), MW–S4I (transition zone), and MW–S4D (bedrock) were collected from June 2003 through September 2004 (figs. 66–68). Fifteen-minute data were collected in Wolf Island Creek from June 2003 through September 2004 (fig. 69). The water-quality data collected

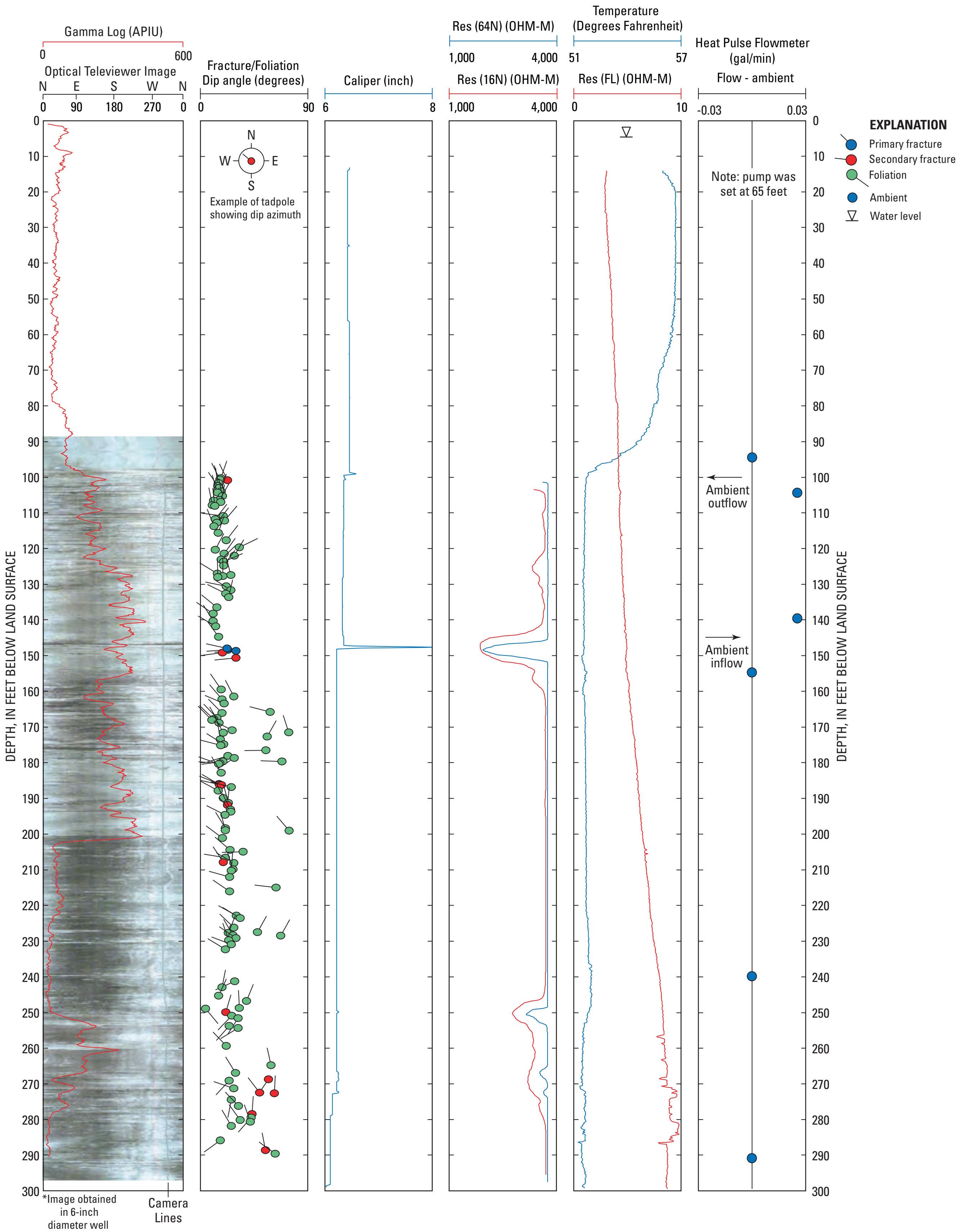

Figure 49. Geophysical logs of bedrock well MW–N1D at the Upper Piedmont research station, North Carolina.

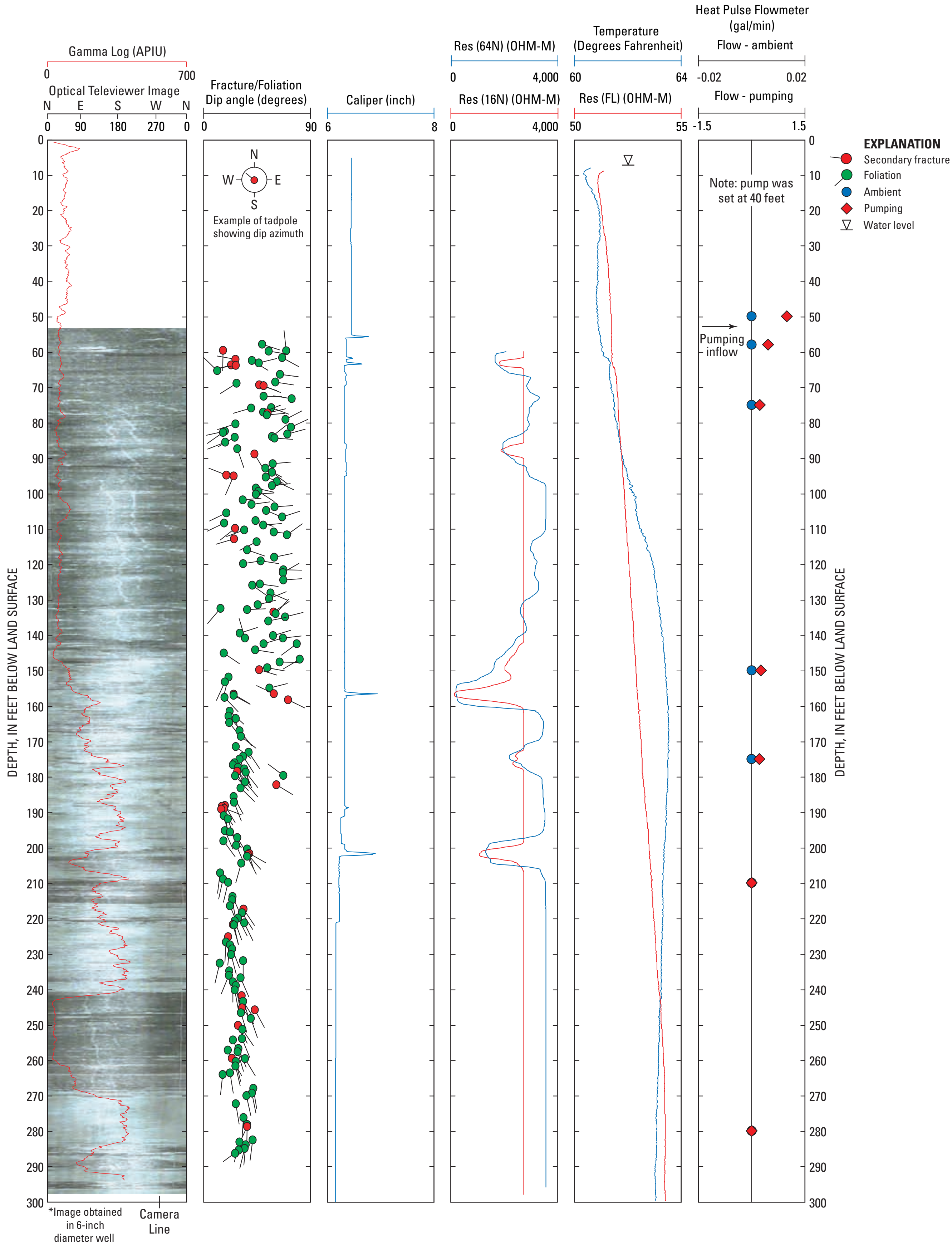

Figure 50. Geophysical logs of bedrock well MW–N2D at the Upper Piedmont research station, North Carolina.

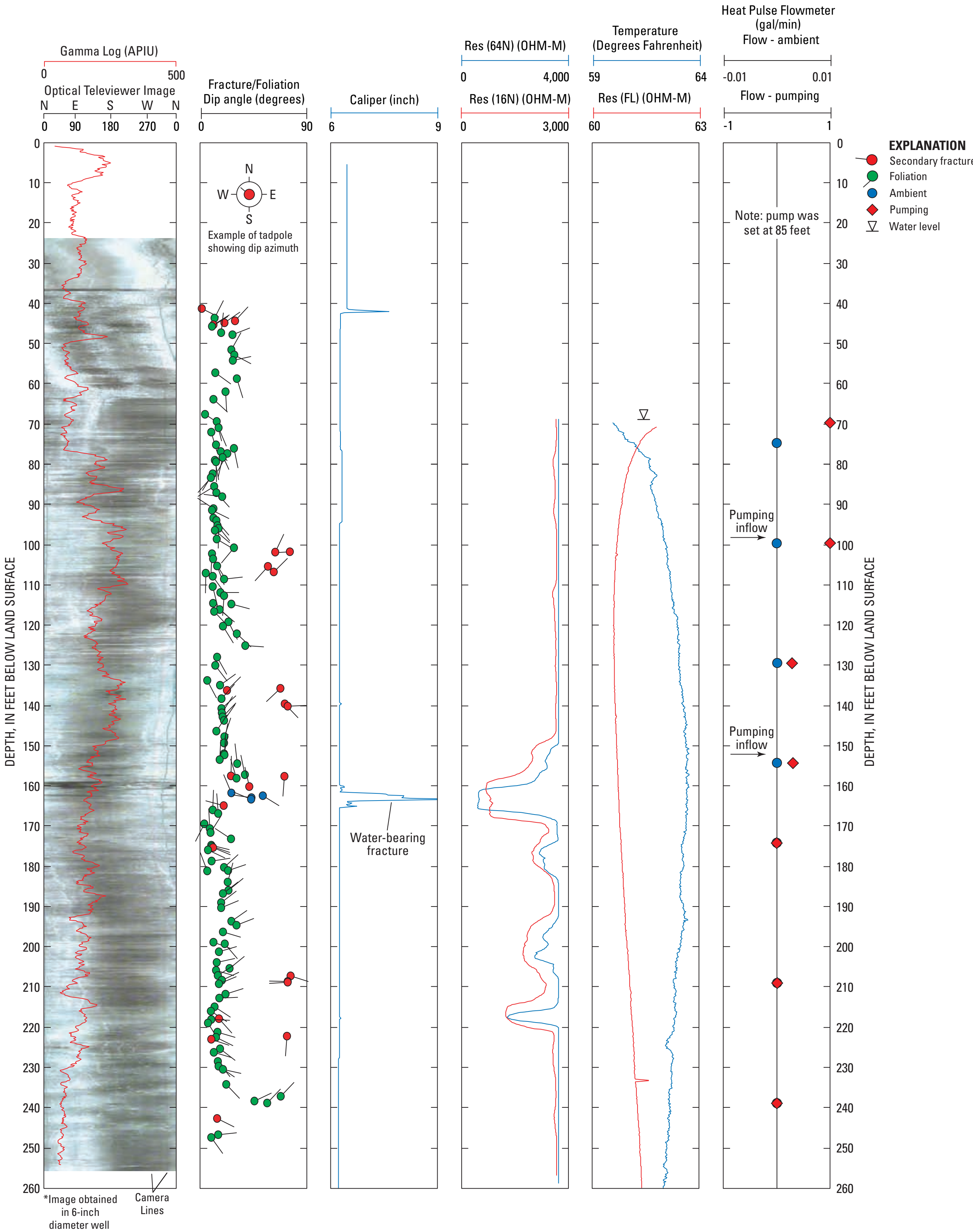

Figure 51. Geophysical logs of bedrock well MW–N3D at the Upper Piedmont research station, North Carolina.

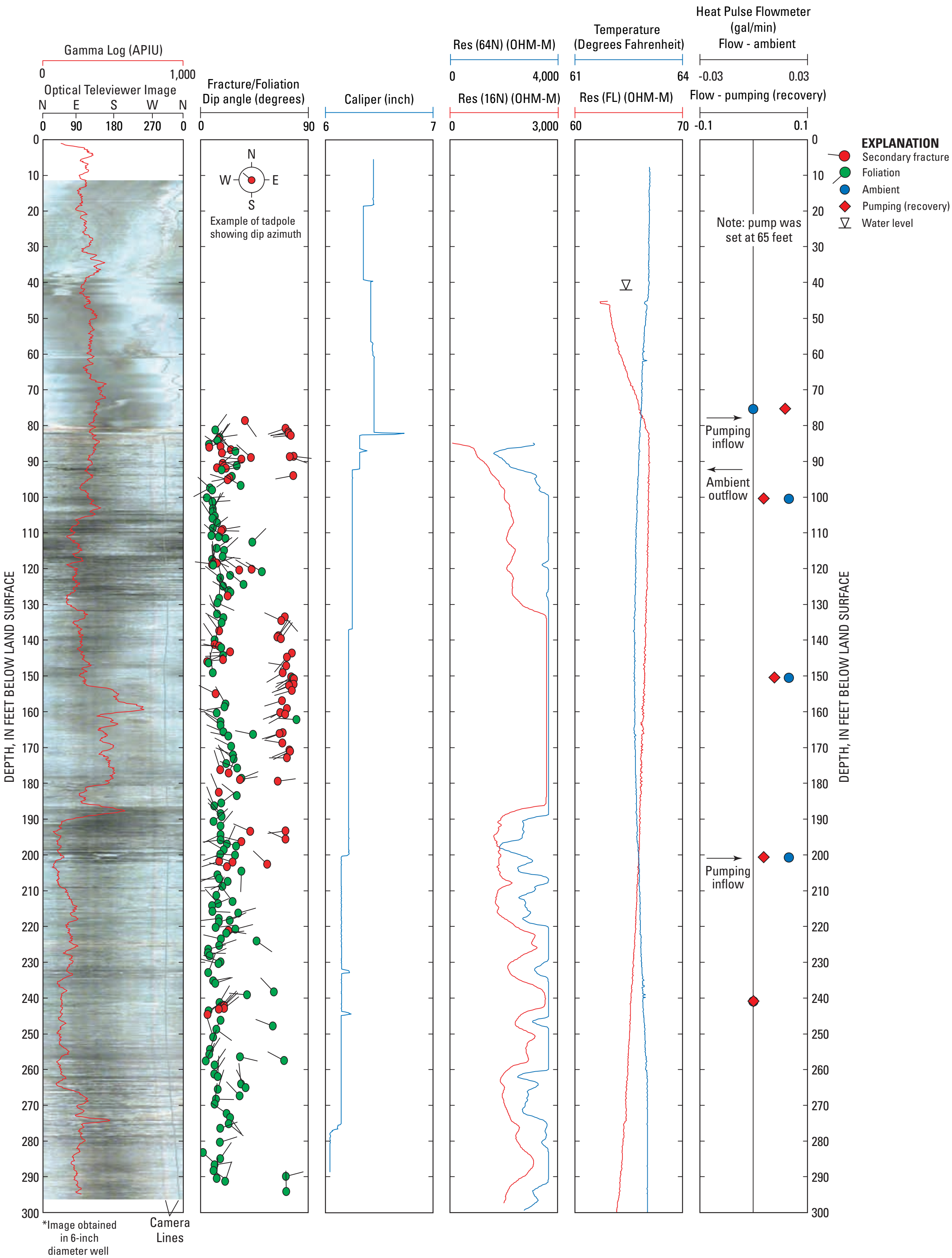

Figure 52. Geophysical logs of bedrock well MW–N4D at the Upper Piedmont research station, North Carolina.

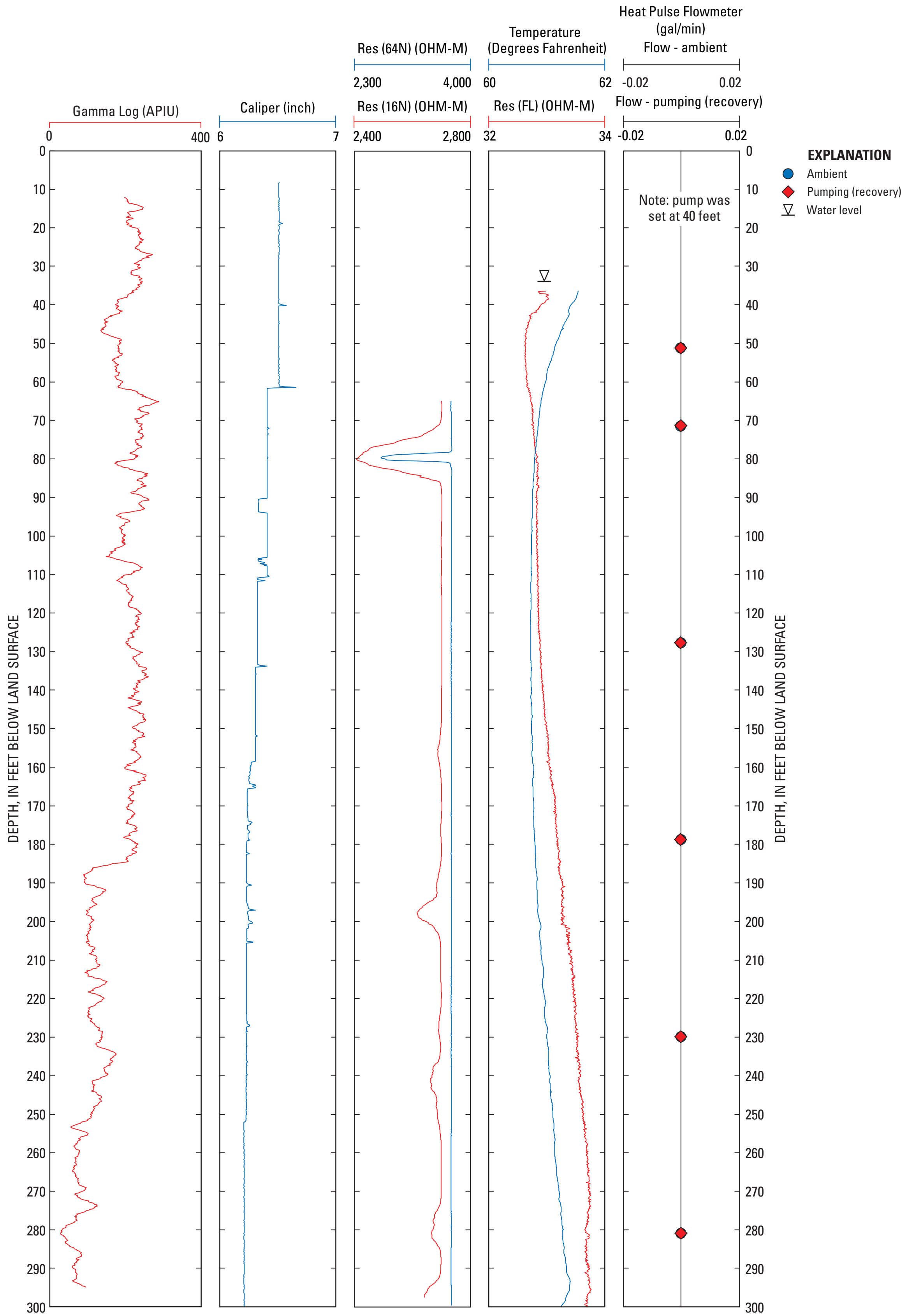

Figure 53. Geophysical logs of bedrock well MW–S1D at the Upper Piedmont research station, North Carolina.

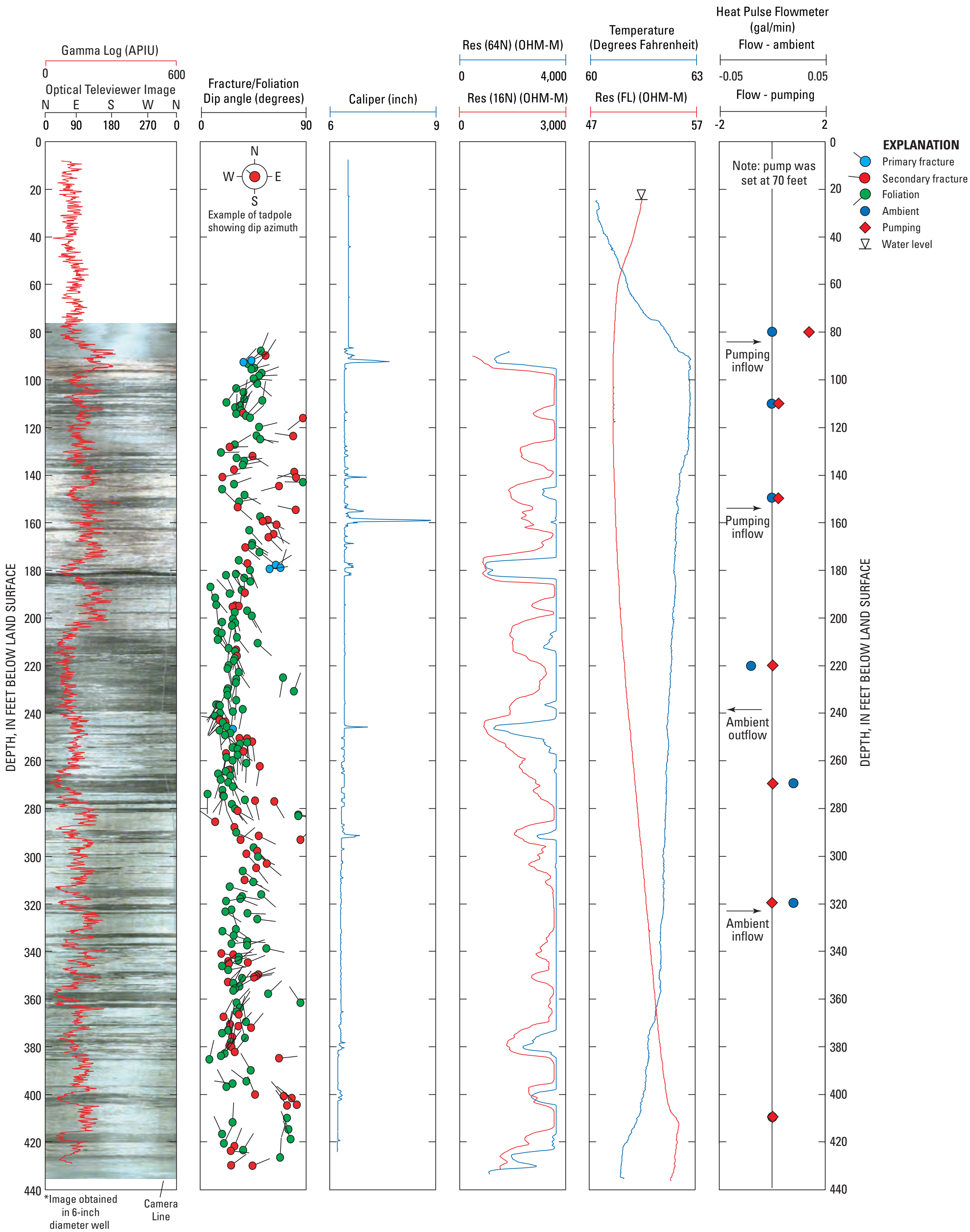

Figure 54. Geophysical logs of bedrock well MW–S3D at the Upper Piedmont research station, North Carolina.

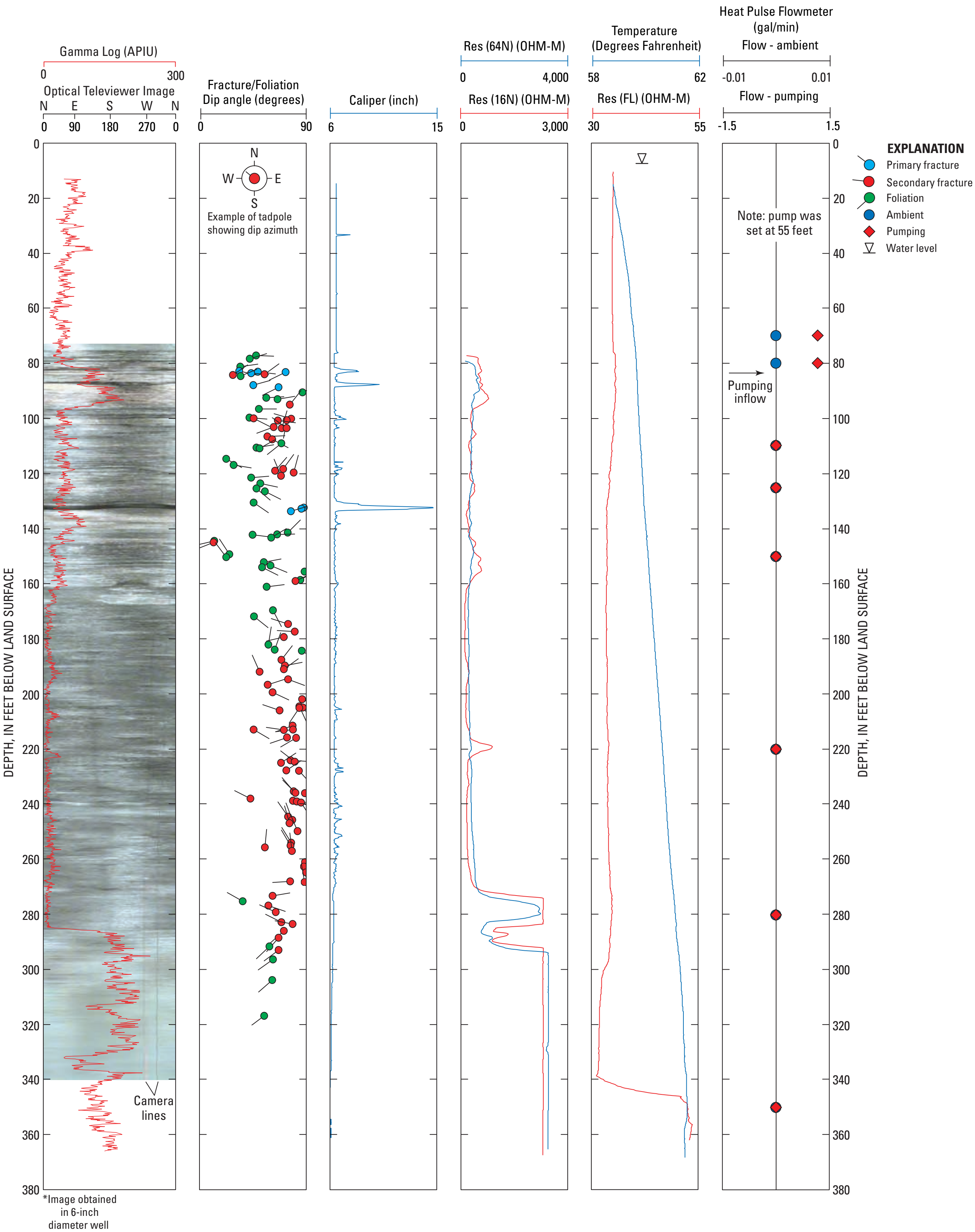

Figure 55. Geophysical logs of bedrock well MW–S4D at the Upper Piedmont research station, North Carolina.

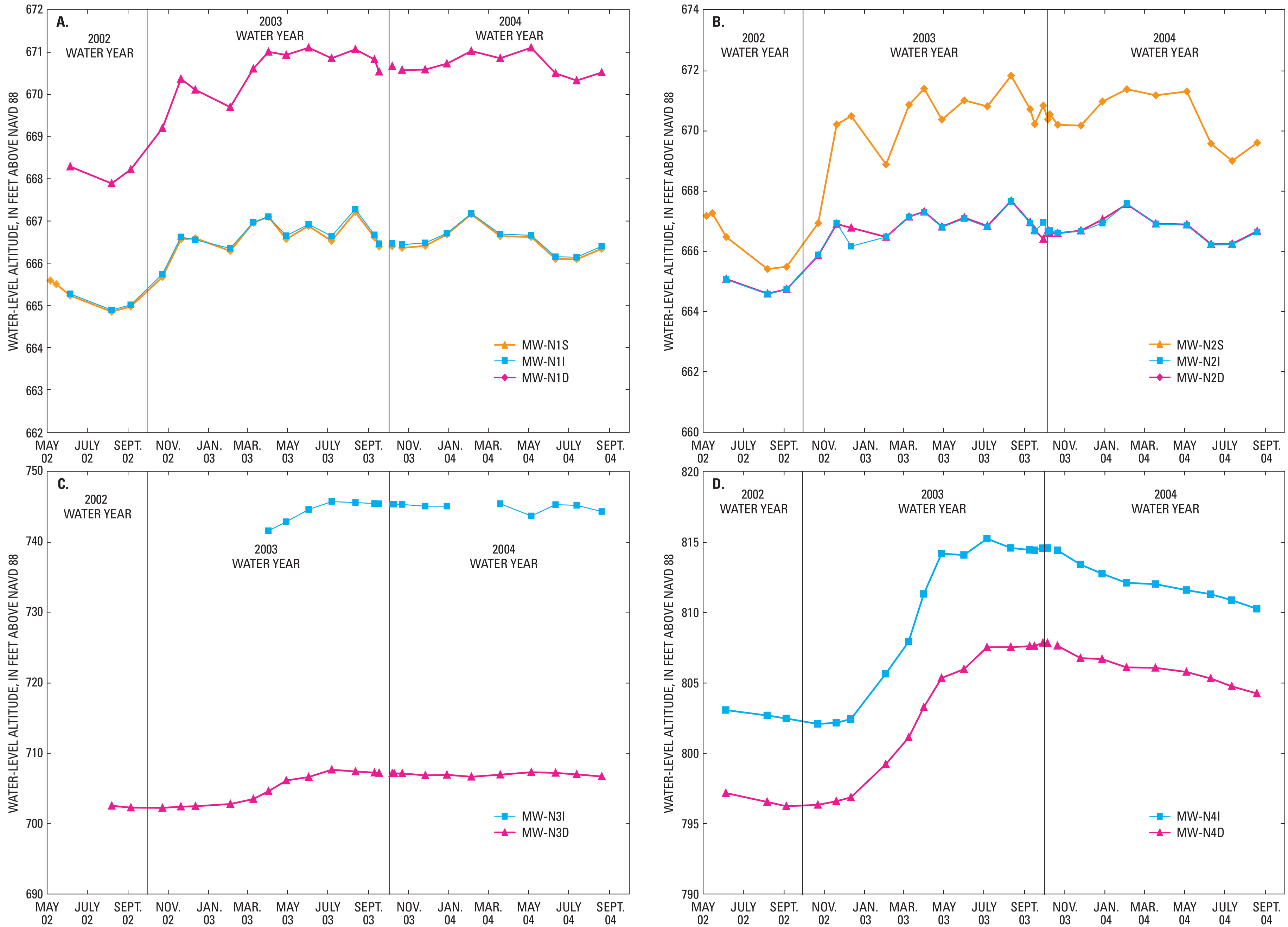

Figure 56. Periodic ground-water levels recorded in well clusters (A) MW–N1, (B) MW–N2, (C) MW–N3, and (D) MW–N4 along the northern transect at the Upper Piedmont research station, North Carolina.

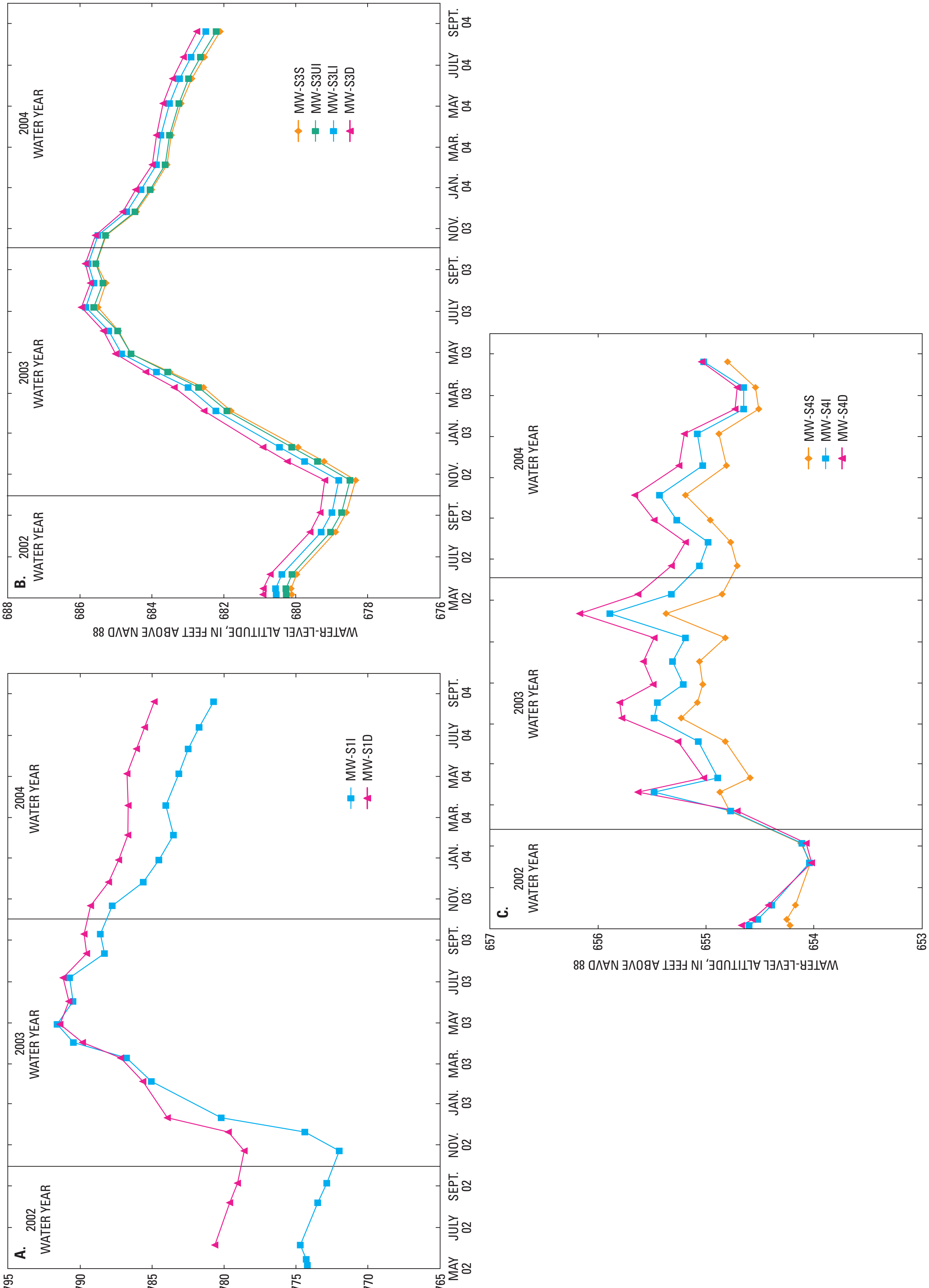

Figure 57. Periodic ground-water levels recorded in well clusters (A) MW–S1, (B) MW–S3, and (C) MW–S4 along the southern transect at the Upper Piedmont research station, North Carolina.

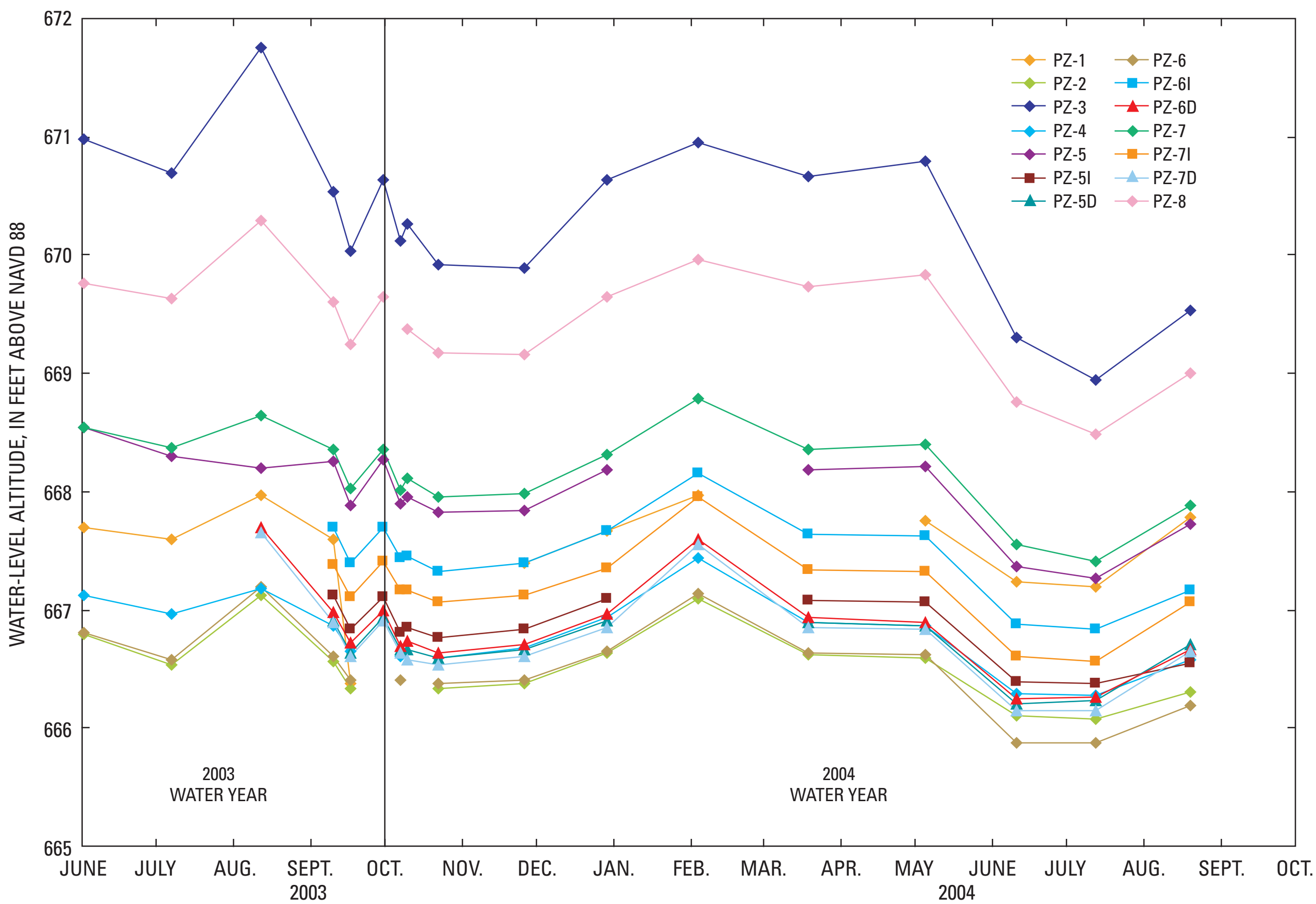

Figure 58. Periodic ground-water levels recorded in piezometers at the Upper Piedmont research station, North Carolina.

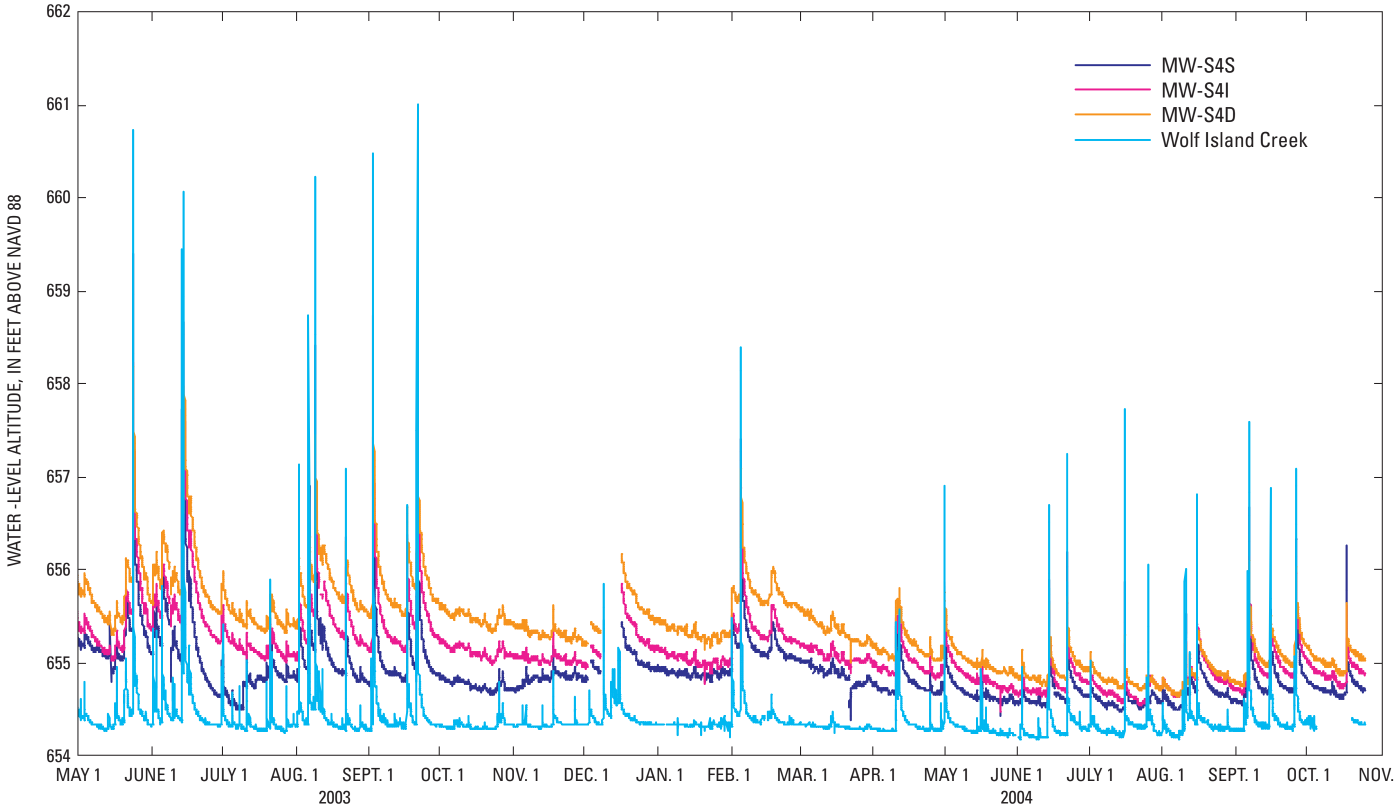

Figure 59. Hourly ground-water levels recorded in well cluster MW–S4 and continuous stage at the streamgaging station at the Upper Piedmont research station, North Carolina, May 2003 through October 2004.

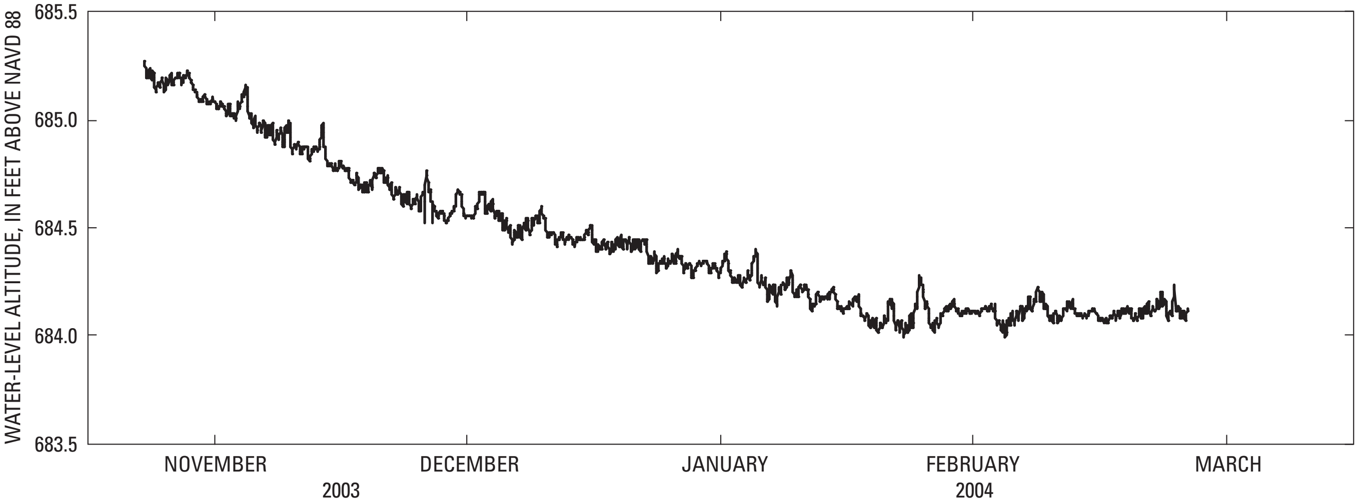

Figure 60. Hourly ground-water levels recorded in bedrock well MW–S3D at the Upper Piedmont research station, North Carolina, November 2003 through March 2004.

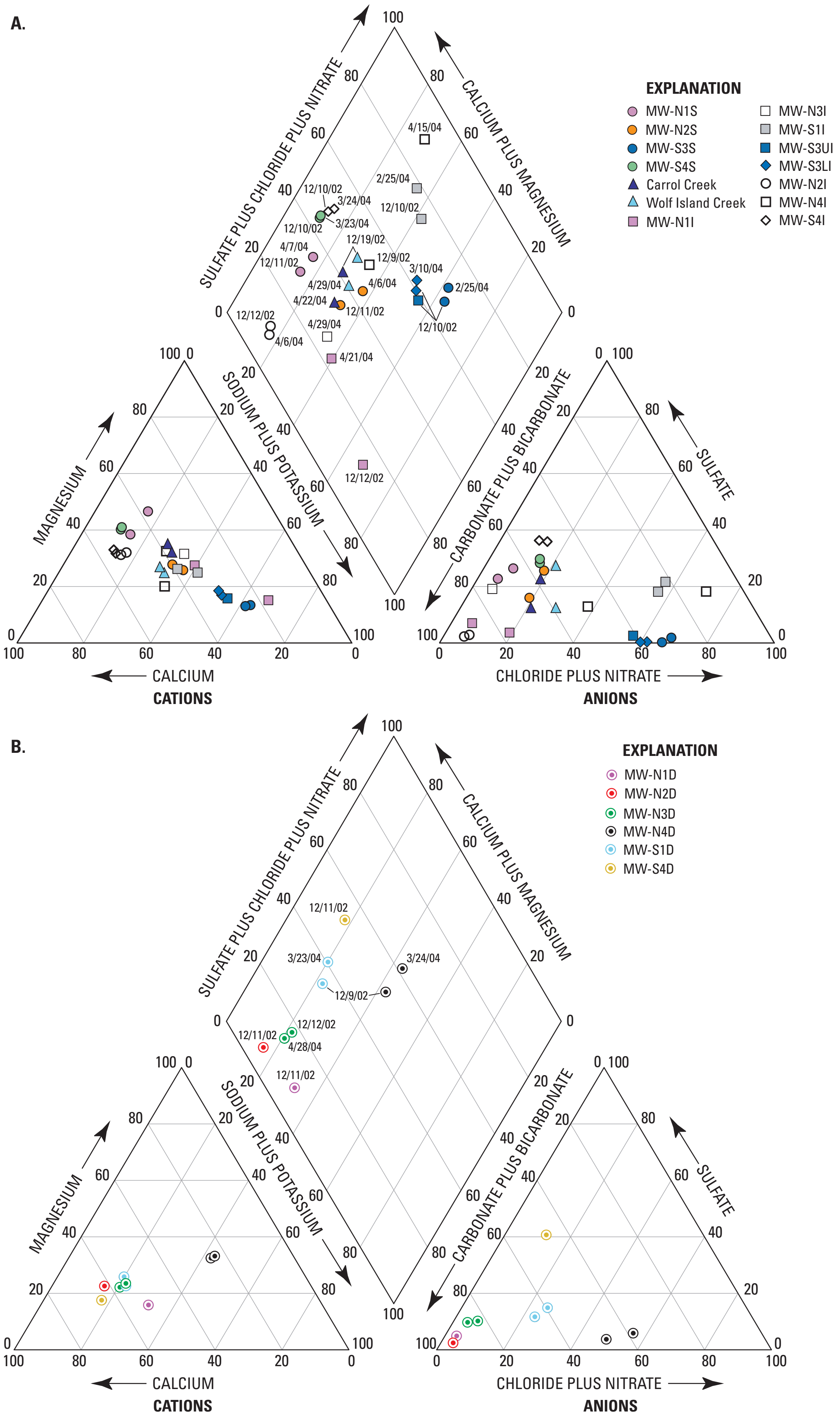

Figure 61. The water chemistry of samples from (A) regolith and transition-zone wells, and surface-water sites, and (B) transition-zone and open-borehole bedrock wells at the Upper Piedmont research station, North Carolina.

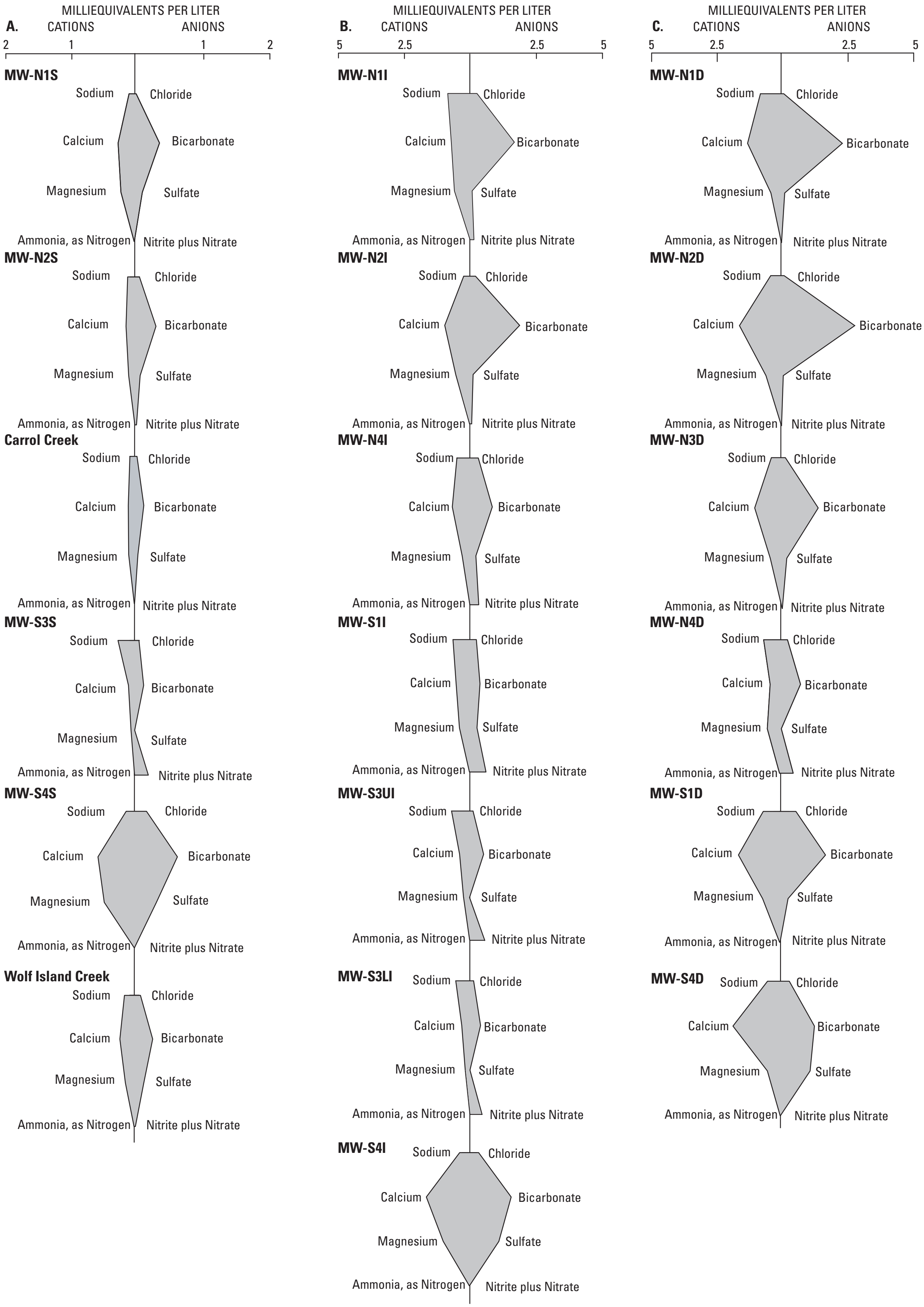

Figure 62. Major ion milliequivalents in water samples collected from (A) regolith wells and the surface-water sites (B) transition-zone wells, and (C) open-borehole bedrock wells at the Upper Piedmont research station, North Carolina, December 2002.

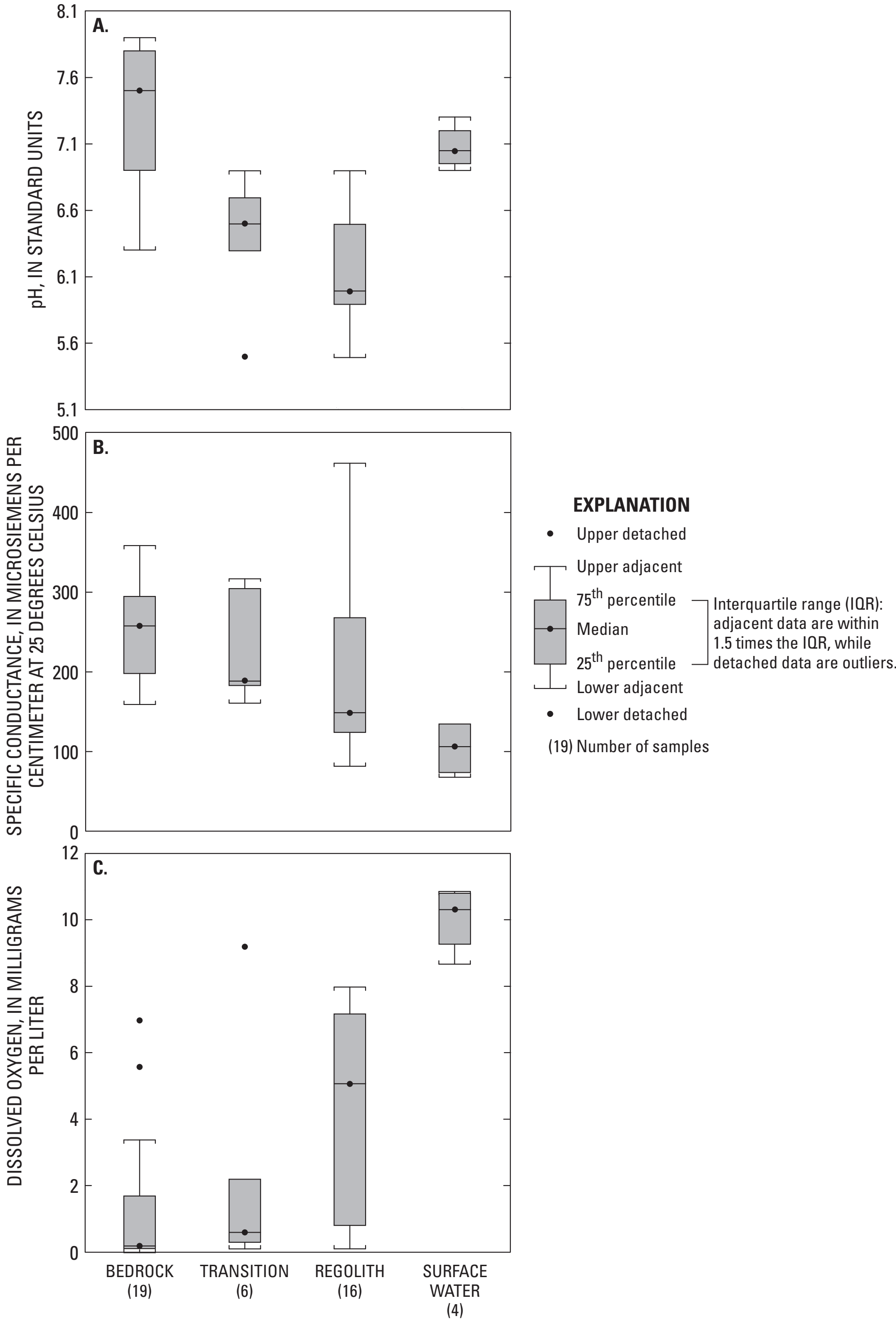

Figure 63. The range, median, and quartile statistical values for (A) pH, (B) specific conductance, and (C) dissolved oxygen for wells and surface-water sites during periodic sampling events at the Upper Piedmont research station, North Carolina.

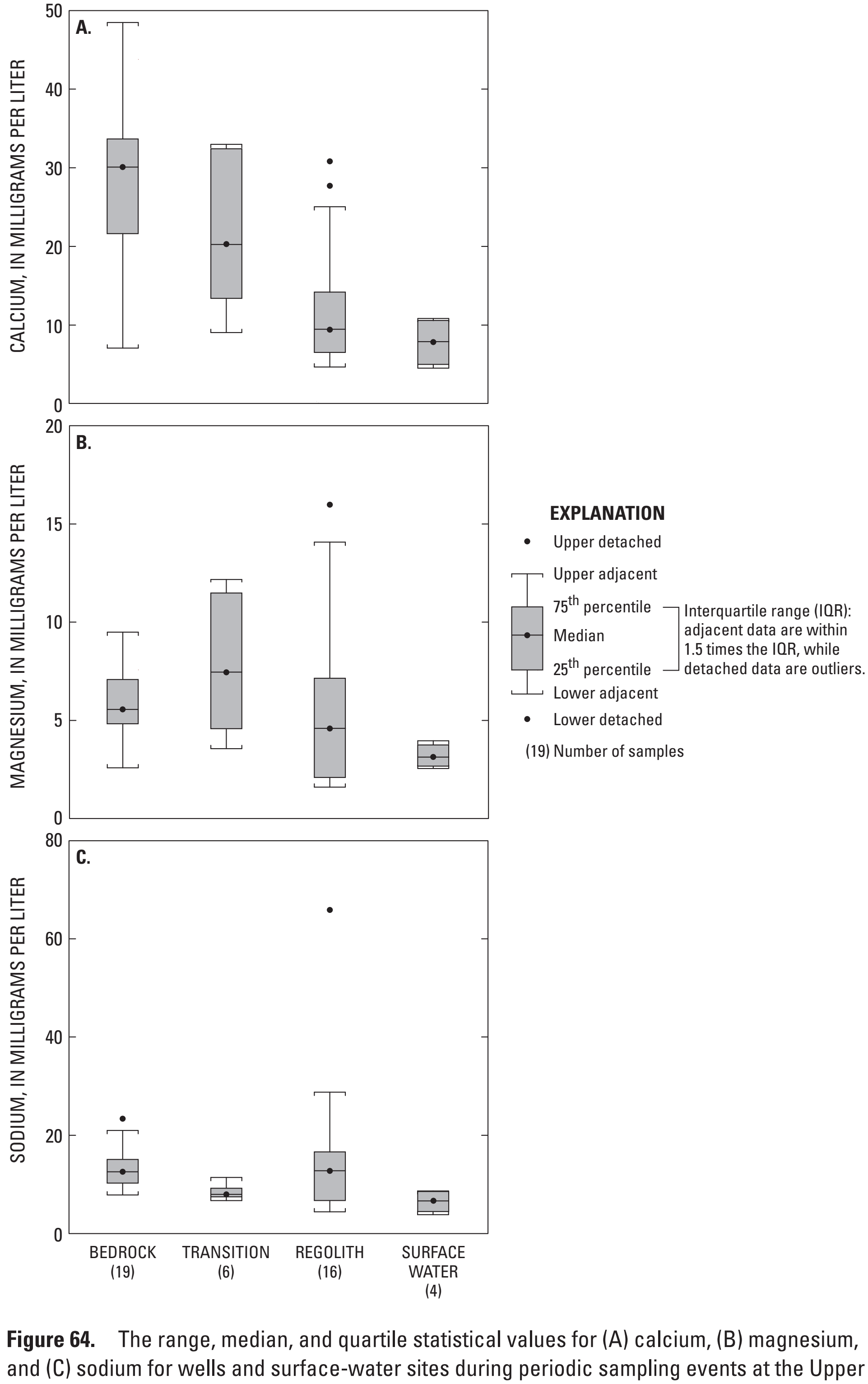

Figure 64. The range, median, and quartile statistical values for (A) calcium, (B) magnesium, and (C) sodium for wells and surface-water sites during periodic sampling events at the Upper Piedmont research station, North Carolina.

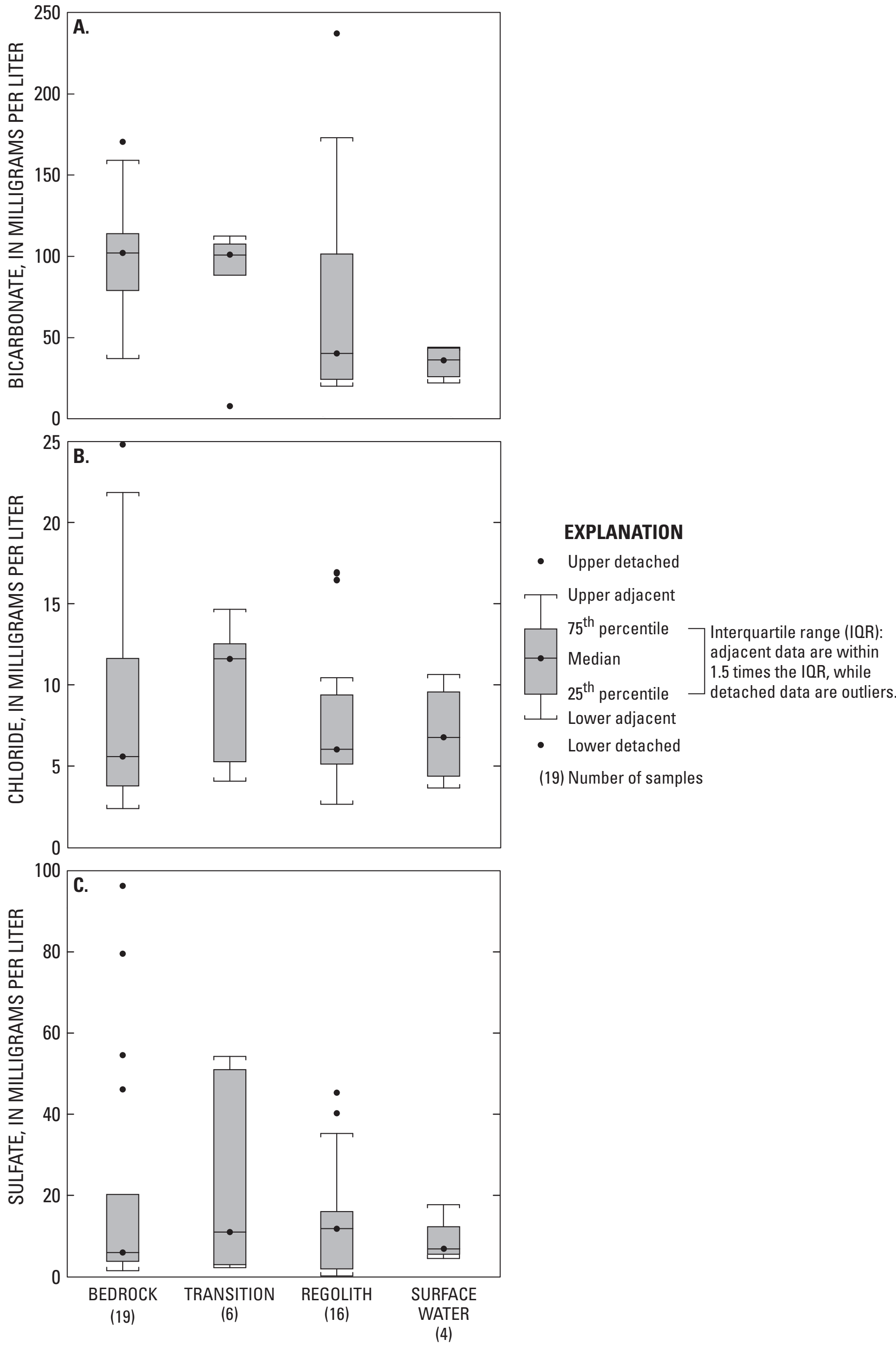

Figure 65. The range, median, and quartile statistical values for (A) bicarbonate, (B) chloride, and (C) sulfate for wells and surface-water sites during periodic sampling events at the Upper Piedmont research station, North Carolina.

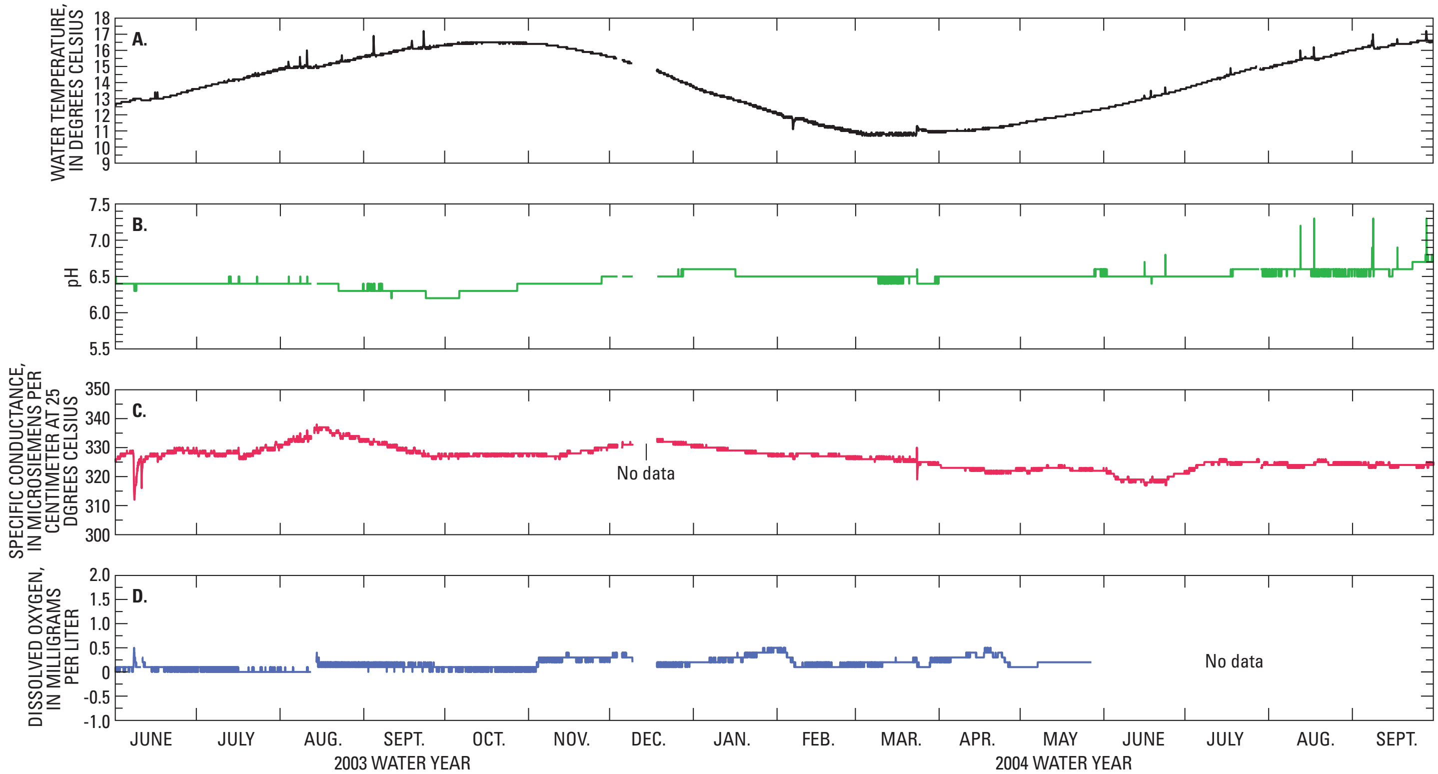

Figure 66. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–S4S in the shallow regolith at the Upper Piedmont research station, North Carolina.

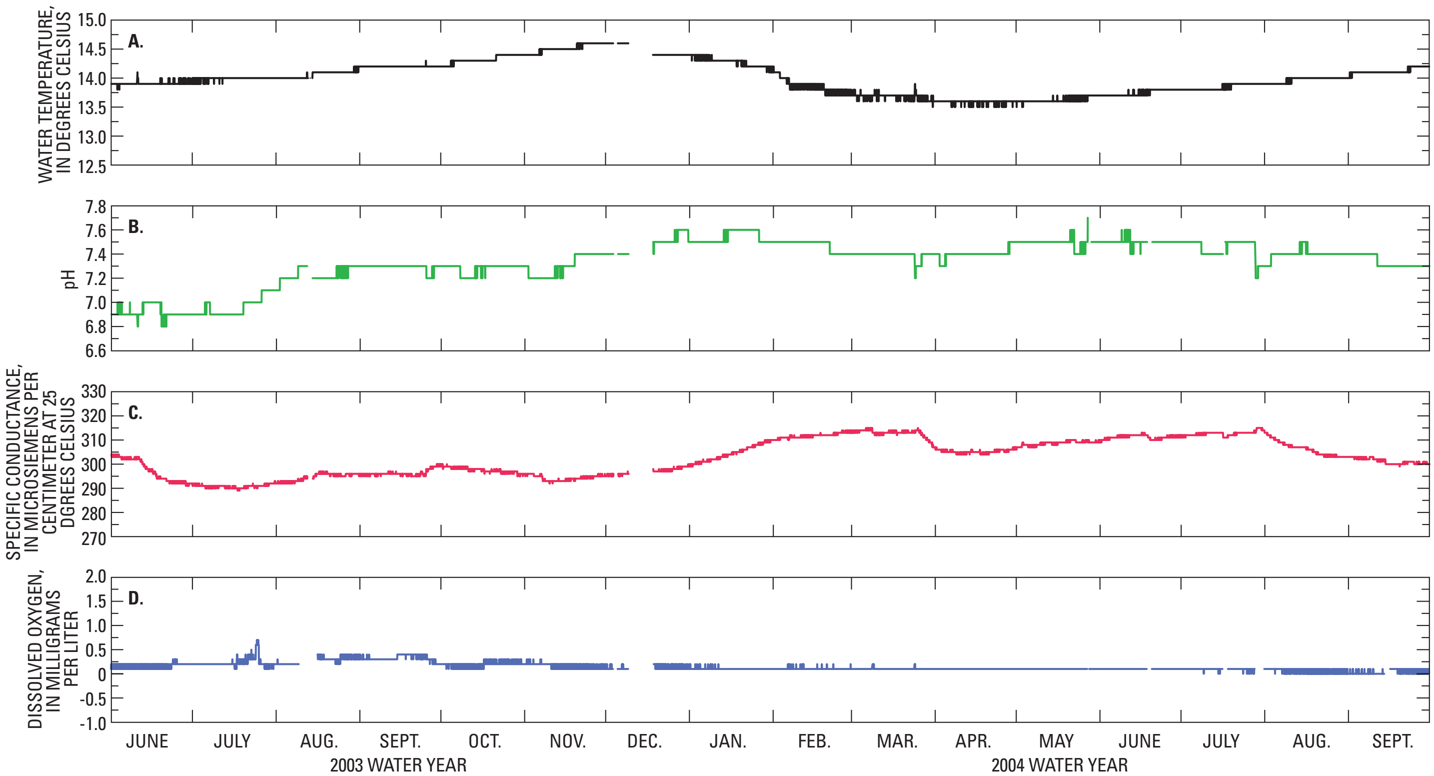

Figure 67. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–S4I in the transition zone at the Upper Piedmont research station, North Carolina.

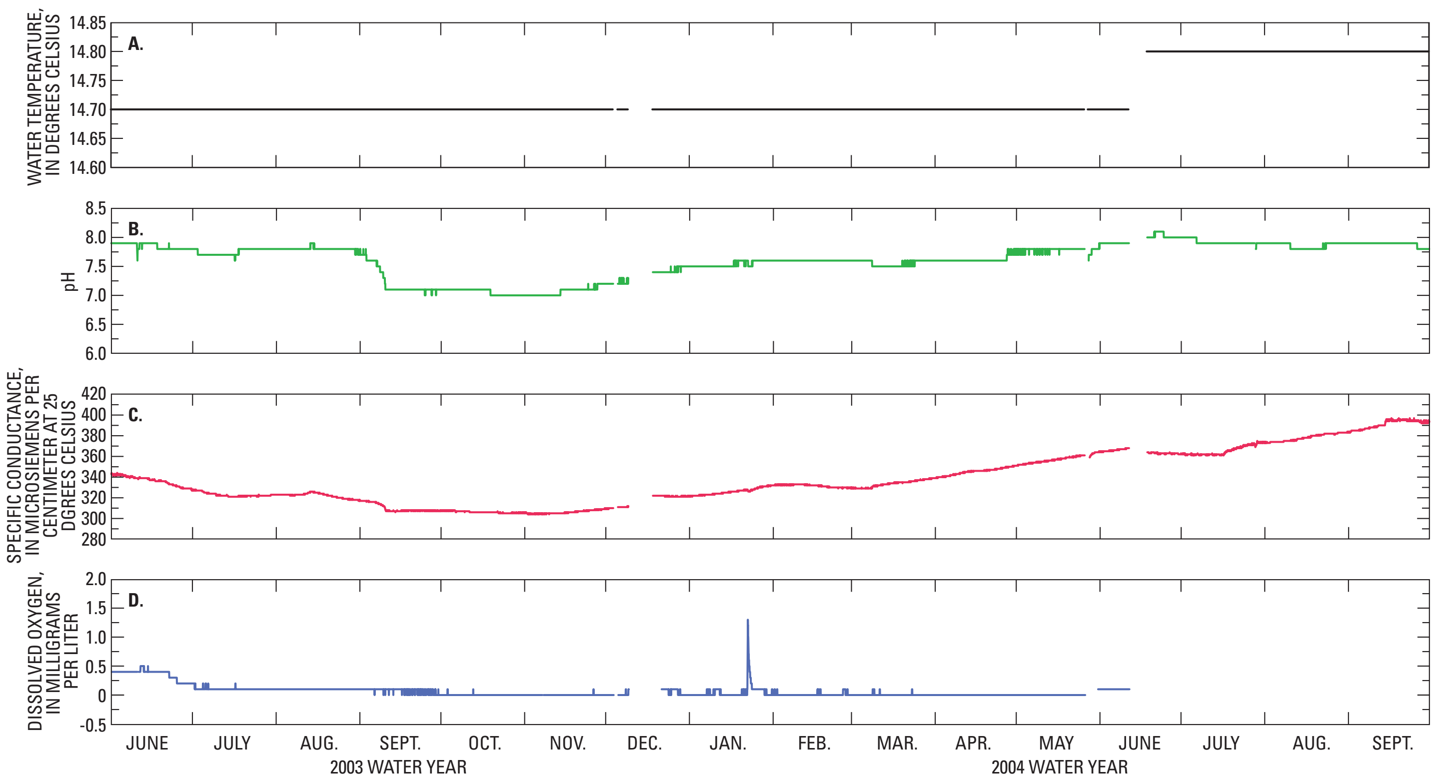

Figure 68. Hourly record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in well MW–S4D in the bedrock at the Upper Piedmont research station, North Carolina.

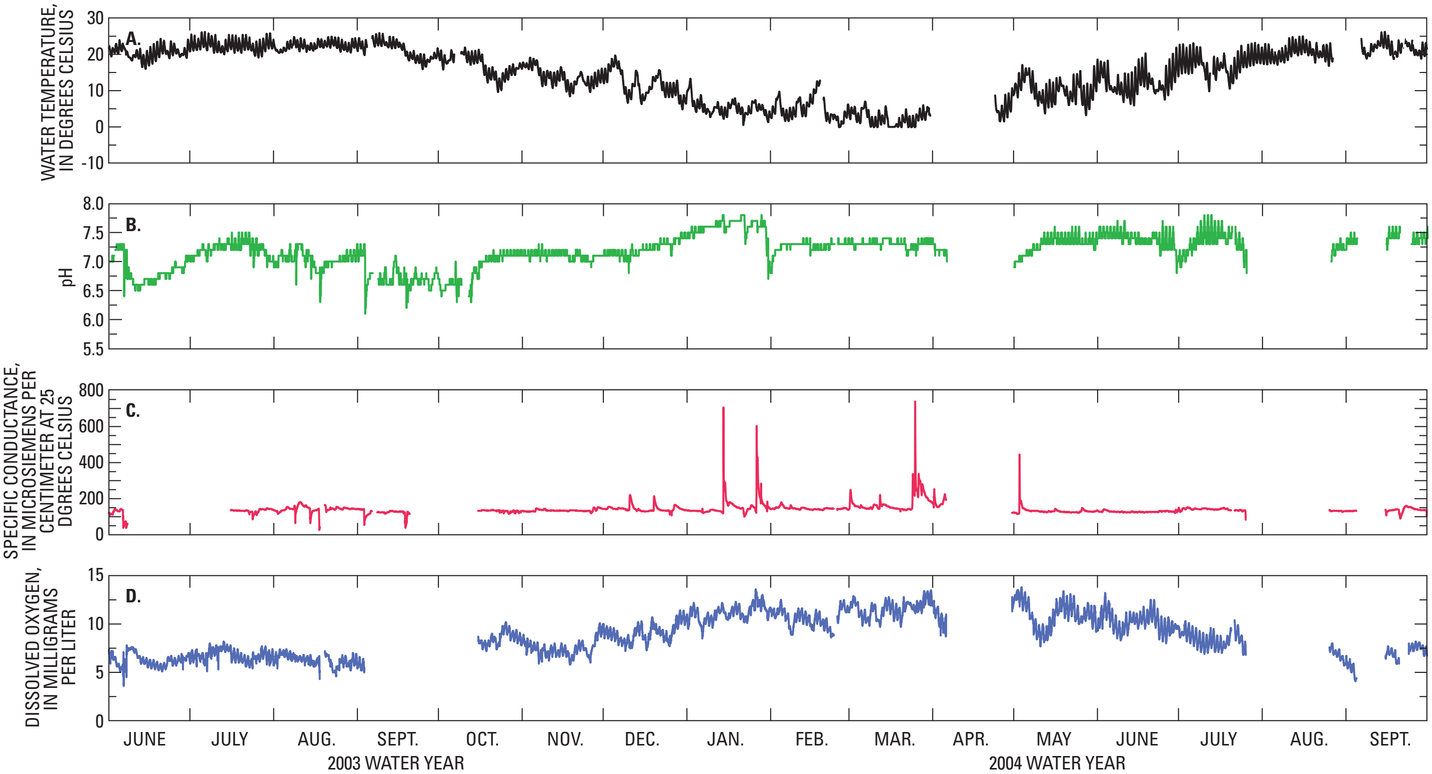

Figure 69. Fifteen-minute record of (A) temperature, (B) pH, (C) specific conductance, and (D) dissolved oxygen in Wolf Island Creek at the Upper Piedmont research station, North Carolina.

were temperature, pH, SC, and DO concentrations. Water temperature at well cluster MW–S4 ranged from about 10.5 to 16.5 °C in the shallow zone, from about 13.5 to 14.5 °C in the transition zone, and from about 14.7 to 14.8 °C in the bedrock zone. Specific conductance ranged from about 320 to 340 μS/cm in the shallow zone, from about 290 to 320 μS/cm in the transition zone, and from about 300 to 400 μS/cm in the bedrock zone. The pH ranged from about 6.3 to 6.7 in the shallow zone, from about 6.8 to 7.6 in the transition zone, and from about 7.0 to 8.0 in the bedrock zone. Dissolved-oxygen concentrations ranged from about 0.1 to 0.5 mg/L in all three zones. Water temperature in Wolf Island Creek ranged from 0 to 25 °C, SC ranged from about 100 to 200 μS/cm, pH ranged from about 6.5 to 7.5, and DO concentrations ranged from about 6 to 12 mg/L.

Bent Creek Research Station

Site Description and Geology

The first hydrogeologic research station installed in the DWQ Asheville Region of North Carolina as part of the PMREP is the Bent Creek research station (BCRS) in Buncombe County (fig. 70). The BCRS is located in the Bent Creek Experimental Forest, which is maintained by the U.S. Department of Agriculture Forest Service. The Bent Creek Experimental Forest is a 5,200-acre tract of land in the Bent Creek valley of the Pisgah National Forest that has been set aside for experimental and demonstration purposes. The BCRS, as defined for this study, consists of approximately 260 acres about 8 miles southwest of the center of Asheville, NC.

The BCRS lies in the Blue Ridge litho-tectonic belt of the Blue Ridge Physiographic Province and is underlain by interlayered and metamorphosed sedimentary and mafic volcanic rock of the Ashe Metamorphic Suite (Merschat and Carter, 2002). Regionally, the hydrogeologic unit map constructed by Daniel and Dahlen (2002) shows the BCRS to be located in the quartzite (QTZ) hydrogeologic unit (fig. 70). Based on geologic coring at the site, however, the BCRS is underlain mainly by interlayered, migmatitic schist and(or) metagraywacke. As mapped by Merschat and Carter (2002), the dominant lithologies at land surface in the Bent Creek drainage basin are garnet-sillimanite-mica-bearing schist, garnet-sillimanite-mica-bearing metasiltstone, and garnet-bearing metagraywacke. Amphibolite and metaconglomerate occur locally but are relatively sparse. Areas of high migmatization occur primarily in the southwestern part of the basin. Other rock bodies in the basin are considered to be minor, discontinuous, and localized. Strong foliation occurs in the schist and metasiltstone; weak or little foliation occurs in the metagraywacke and migmatite. Work that has been conducted from July 2002 to September 2004 at the BCRS includes the collection and logging of seven soil and rock cores totaling 830 ft, installation of 18 monitoring wells grouped into six clusters along a transect, installation of 15 piezometers for water-level and aquifer-test monitoring, installation of a real-time DCP for continuous monitoring of water levels and water quality in a three-well cluster and the adjacent stream, monthly collection of water levels, semiannual sampling of wells, slug tests, 72-hour aquifer test, and borehole geophysical logs.

Well Construction

During this investigation, six ground-water monitoring-well clusters, consisting of three wells each along with 15 piezometers were constructed at the BCRS (fig. 71; table 7). The piezometers were arranged in seven clusters, each consisting of one well in the shallow regolith and one well in the transition zone with the exception of PZ–3S, which was not paired with a transition-zone well. Well cluster locations were selected to obtain water-quality and water-level data along a topographic transect encompassing areas of recharge and discharge based on conceptual models developed for the slope-aquifer system (LeGrand and Nelson, 2004). Criteria for well locations included topographic setting, accessibility, and site boundaries. Cross section A–A' was constructed along the well transect from well cluster MW–7, located in a conceptual recharge area, to well cluster MW–2, located in a discharge area near two streams—Boyd Branch and Bent Creek (figs. 71, 72).

Each well cluster at the BCRS consists of three wells—a shallow water-level well to monitor ground-water conditions in the regolith, a transition-zone well to monitor ground-water conditions in the partially weathered rock and open fractures near the top of bedrock, and a deeper bedrock well to monitor ground water in the fractured bedrock aquifer (fig. 72). Well-construction information is provided in table 7.

Water-Resources Data

Borehole geophysical logs were collected from all six bedrock wells at the BCRS. Data collected from these wells include caliper, natural gamma, short-normal and long-normal resistivity logs; fluid-temperature and fluid-resistivity logs; heat-pulse flowmeter data (both ambient and stressed conditions); and OTV images (figs. 73–78).

Monthly water levels have been measured in all 18 wells since February 2003 at the BCRS (fig. 79). The period of record discussed in this report is February 2003 through September 2004. Ground-water altitudes at well cluster MW–1 ranged from about 2,197 to 2,198 ft in the shallow zone, from about 2,197 to 2,199 ft in the transition zone, and from about 2,196 to 2,199 ft in the bedrock zone. The water-level altitudes in the transition zone were consistently higher than water-level altitudes in the shallow and bedrock zones at well cluster MW–1. Ground-water altitudes at well

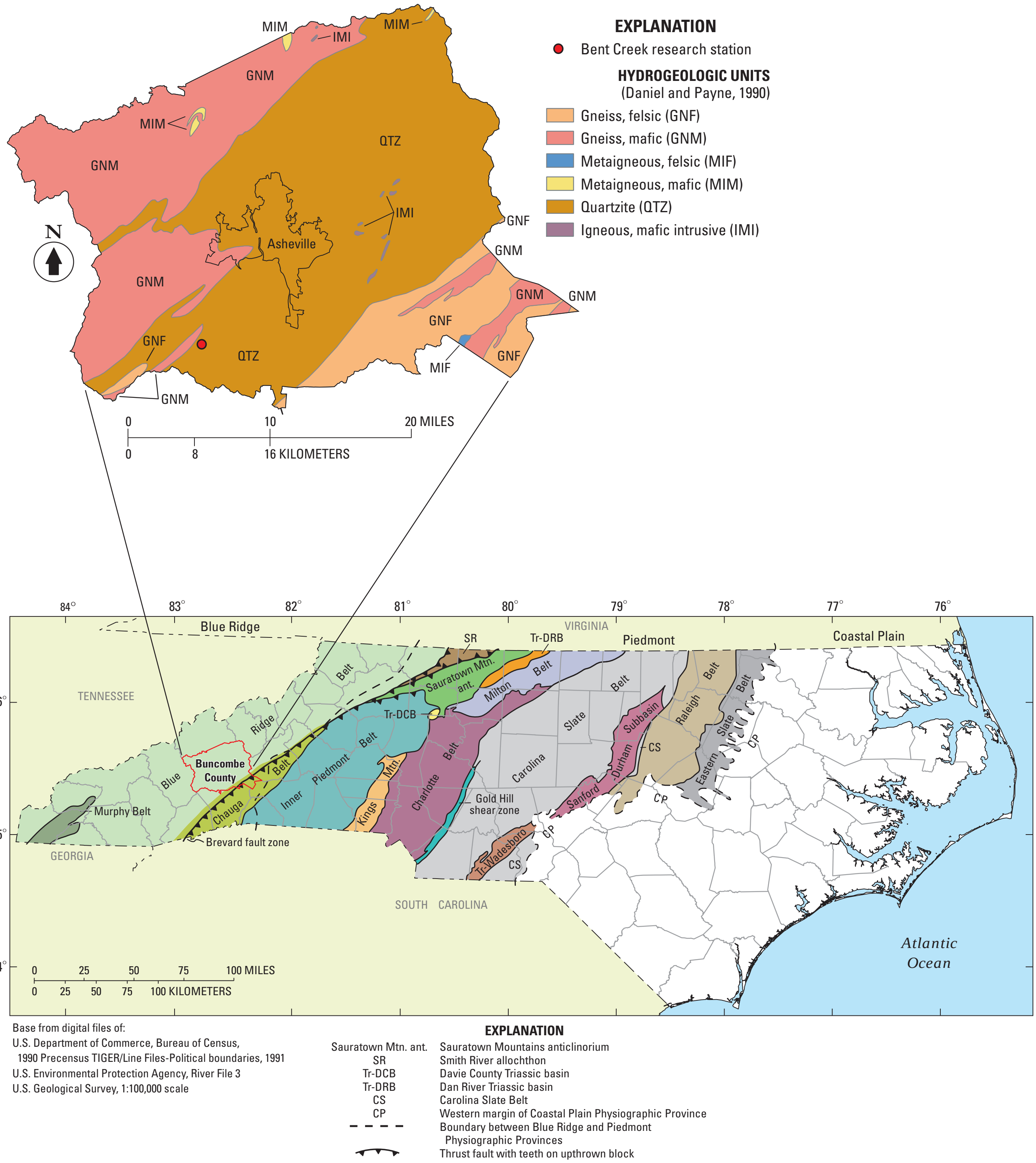

Figure 70. Locations of Bent Creek research station, hydrogeologic units in Buncombe County, and geologic belts delineated in North Carolina (modified from North Carolina Geological Survey, 1985; Daniel and Payne, 1990).

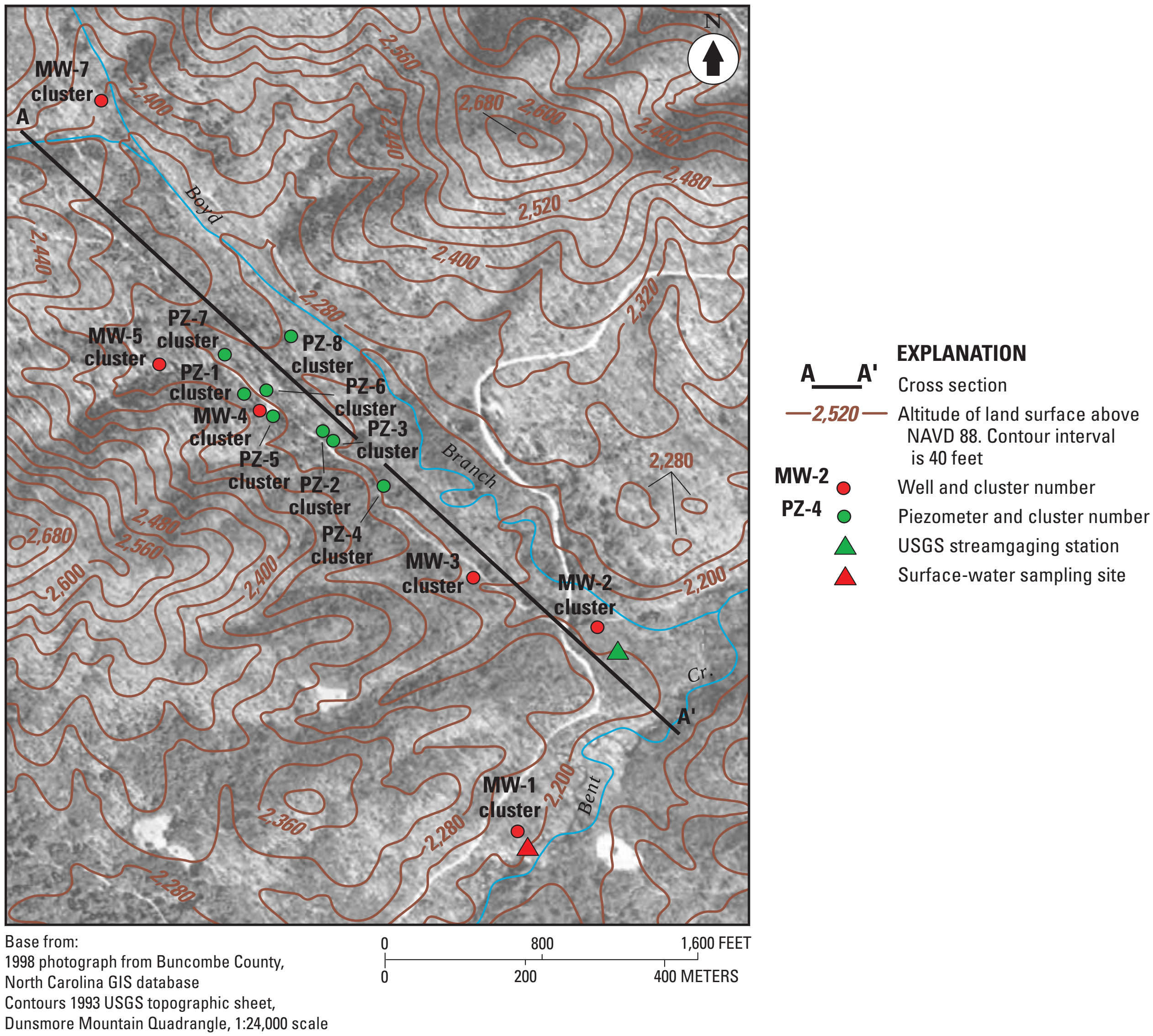

Figure 71. Aerial photograph overlaid with topographic features showing locations of well clusters, surface-water sites, and line of section A–A′ at the Bent Creek research station in Buncombe County, North Carolina.

Table 7. Construction characteristics of monitoring wells and the surface-water site at the Bent Creek Research Station, North Carolina.

[NAVD 88, North American Vertical Datum of 1988; MW, monitoring well; S, shallow; PVC, polyvinyl chloride casing; R, regolith; I, transition zone; D, deep; B, bedrock; PZ, piezometer; na, not applicable; SW, surface water]

Site identification	Station name	Construction date	Land-surface altitude (feet above NAVD 88)	Casing material	Casing diameter (inches)	Screened interval or open borehole interval (feet below land surface)		Screen type	Zone monitored
						from	to		
352840082381001	MW–1S	10/17/2002	2,200.99	PVC	4.0	8	22	0.01 slotted PVC	R
352840082381002	MW–1I	10/16/2002	2,202.52	PVC	4.0	38	53	0.01 slotted PVC	I
352840082381003	MW–1D	10/8/2002	2,201.77	PVC	6.0	55	221	Open hole	B
352854082380501	MW–2S	10/30/2002	2,190.69	PVC	4.0	5	20	0.01 slotted PVC	R
352854082380502	MW–2I	10/24/2002	2,191.72	PVC	4.0	21	36	0.01 slotted PVC	I
352854082380503	MW–2D	10/22/2002	2,190.15	PVC	6.0	53	300	Open hole	B
352856082381201	MW–3S	10/3/2002	2,210.12	PVC	4.0	15	30	0.01 slotted PVC	R
352856082381202	MW–3I	10/3/2002	2,209.45	PVC	4.0	35	50	0.01 slotted PVC	I
352856082381203	MW–3D	9/17/2002	2,209.07	PVC	6.0	61	300	Open hole	B
352808082382601	MW–4S	9/12/2002	2,259.66	PVC	4.0	7	22	0.01 slotted PVC	R
352808082382602	MW–4I	9/11/2002	2,258.80	PVC	4.0	26	41	0.01 slotted PVC	I
352808082382603	MW–4D	8/29/2002	2,258.53	PVC	6.0	61	501	Open hole	B
352810082383501	MW–5S	8/8/2002	2,299.99	PVC	4.0	9	24	0.01 slotted PVC	R
352810082383502	MW–5I	8/22/2002	2,302.19	PVC	4.0	32	47	0.01 slotted PVC	I
352810082383503	MW–5D	8/12/2002	2,304.84	PVC	6.0	62	300	Open hole	B
352827082383901	MW–7S	7/17/2002	2,368.23	PVC	4.0	10	25	0.01 slotted PVC	R
352827082383902	MW–7I	7/16/2002	2,369.04	PVC	4.0	30	50	0.01 slotted PVC	I
352827082383903	MW–7D	7/9/2002	2,369.88	PVC	6.0	62	285	Open hole	B
352909082382801	PZ–1S	6/16/2004	2,260[a]	PVC	2.0	12	17	0.01 slotted PVC	R
352909082382802	PZ–1I	6/15/2004	2,260[a]	PVC	2.0	25	30	0.01 slotted PVC	I
352907082382501	PZ–2S	6/22/2004	2,255[a]	PVC	2.0	17	22	0.01 slotted PVC	R
352907082382502	PZ–2I	6/23/2004	2,255[a]	PVC	2.0	54	59	0.01 slotted PVC	I
352907082382401	PZ–3S	6/23/2004	2,254[a]	PVC	2.0	17	22	0.01 slotted PVC	R
352904082382001	PZ–4S	6/24/2004	2,235[a]	PVC	2.0	12	17	0.01 slotted PVC	R
352904082382002	PZ–4I	6/24/2004	2,235[a]	PVC	2.0	25	30	0.01 slotted PVC	I
352908082382701	PZ–5S	6/30/2004	2,260[a]	PVC	2.0	12	17	0.01 slotted PVC	R
352908082382702	PZ–5I	6/30/2004	2,260[a]	PVC	2.0	24	29	0.01 slotted PVC	I
352909082382701	PZ–6S	7/13/2004	2,260[a]	PVC	2.0	17	22	0.01 slotted PVC	R
352909082382702	PZ–6I	7/1/2004	2,260[a]	PVC	2.0	29	34	0.01 slotted PVC	I
352911082383101	PZ–7S	7/14/2004	2,275[a]	PVC	2.0	8	13.5	0.01 slotted PVC	R
352911082383102	PZ–7I	7/20/2004	2,275[a]	PVC	2.0	20	25	0.01 slotted PVC	I
352912082382601	PZ–8S	7/14/2004	2,260[a]	PVC	2.0	15	20	0.01 slotted PVC	R
352912082382602	PZ–8I	7/14/2004	2,260[a]	PVC	2.0	29	34	0.01 slotted PVC	I
0344789265	Boyd Branch	3/17/2004	2,190	na	na	na	na	na	SW

[a]Piezometer altitudes from U.S. Geological Survey 7.5-minute topographic quadrangle map (+/– 10 feet).

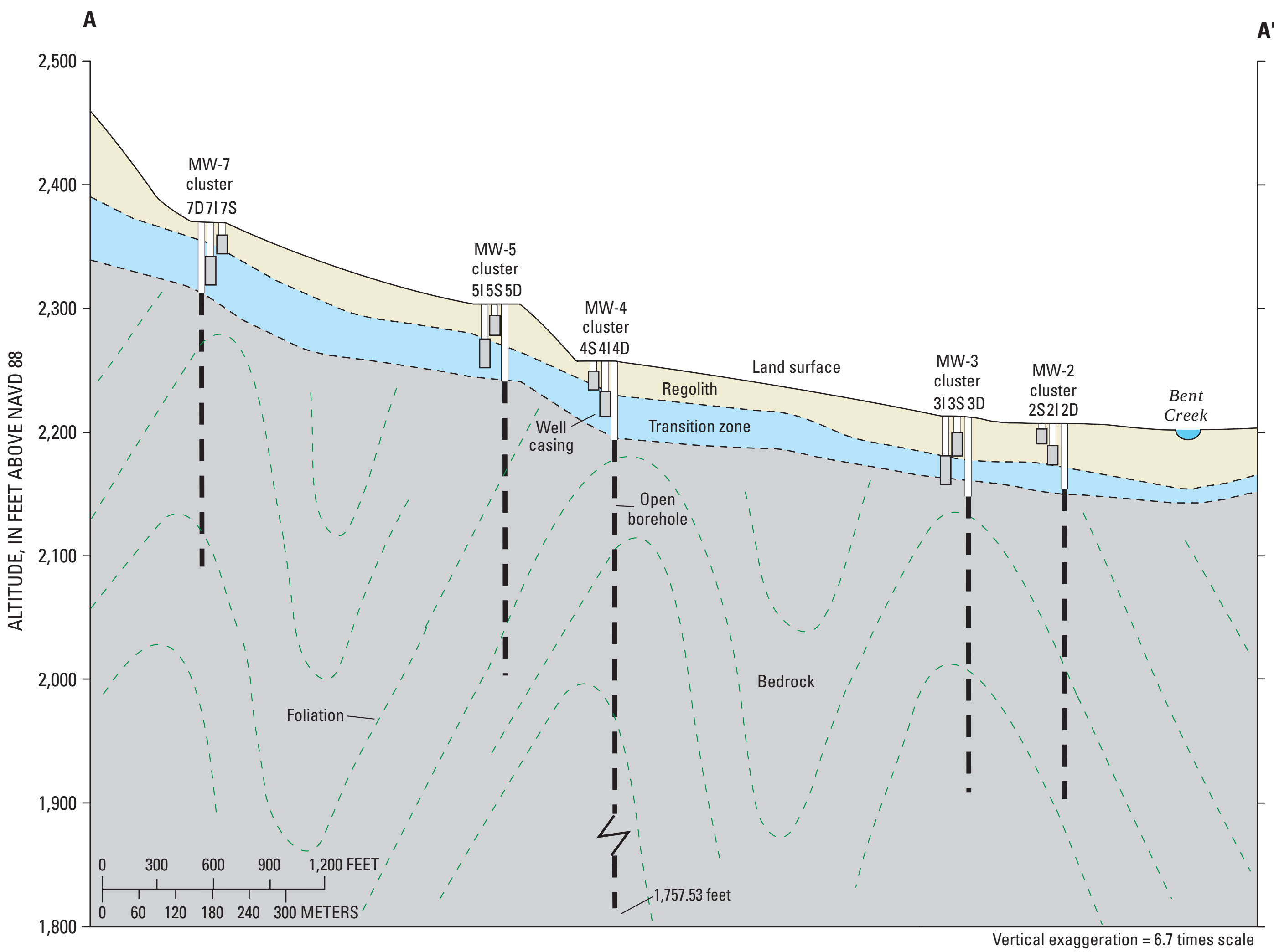

Figure 72. Generalized hydrogeologic cross section A–A′ along the well transect at the Bent Creek research station, North Carolina (section location is shown in figure 71).

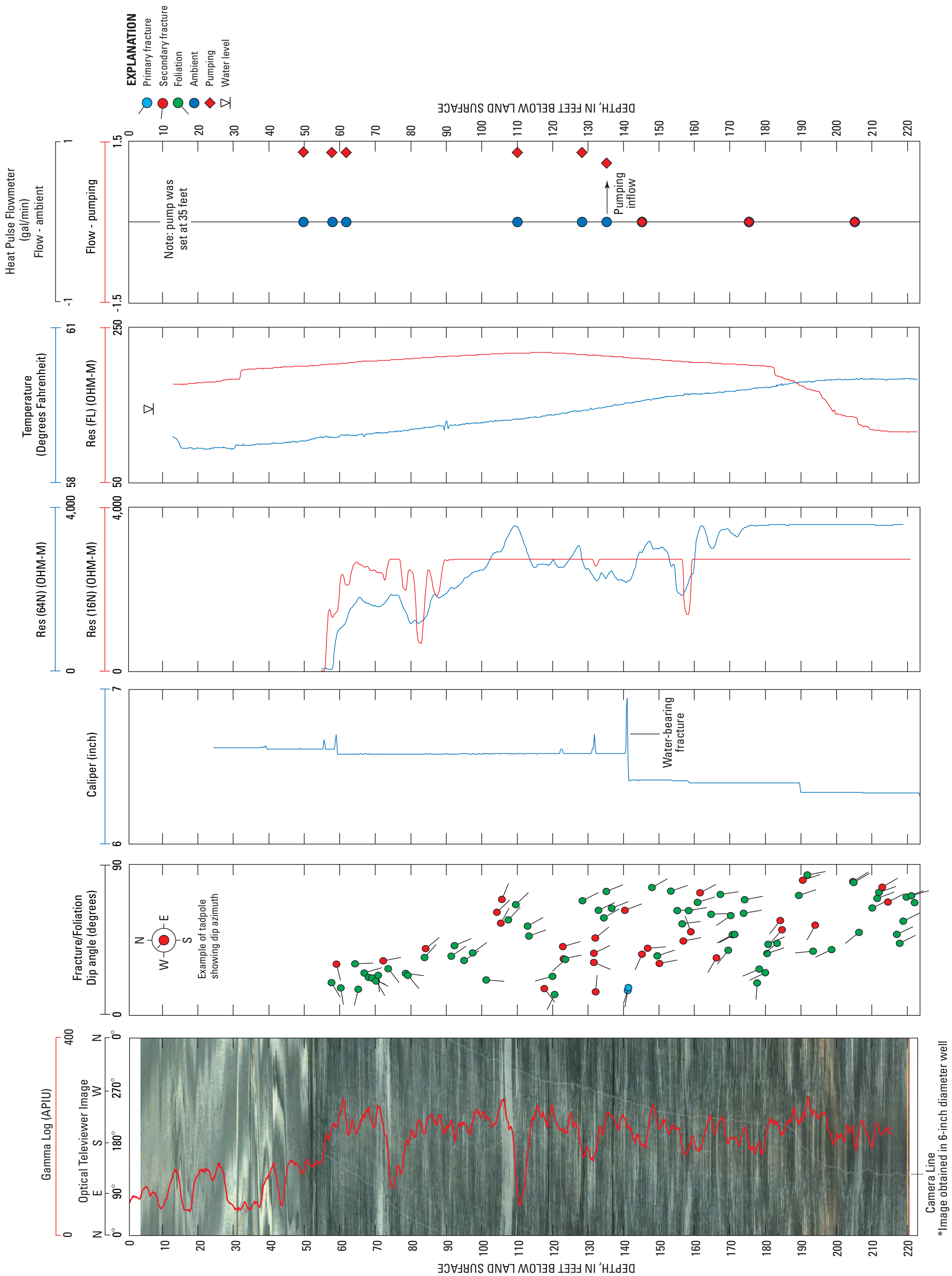

Figure 73. Geophysical logs of bedrock well MW–1D at the Bent Creek research station, North Carolina.

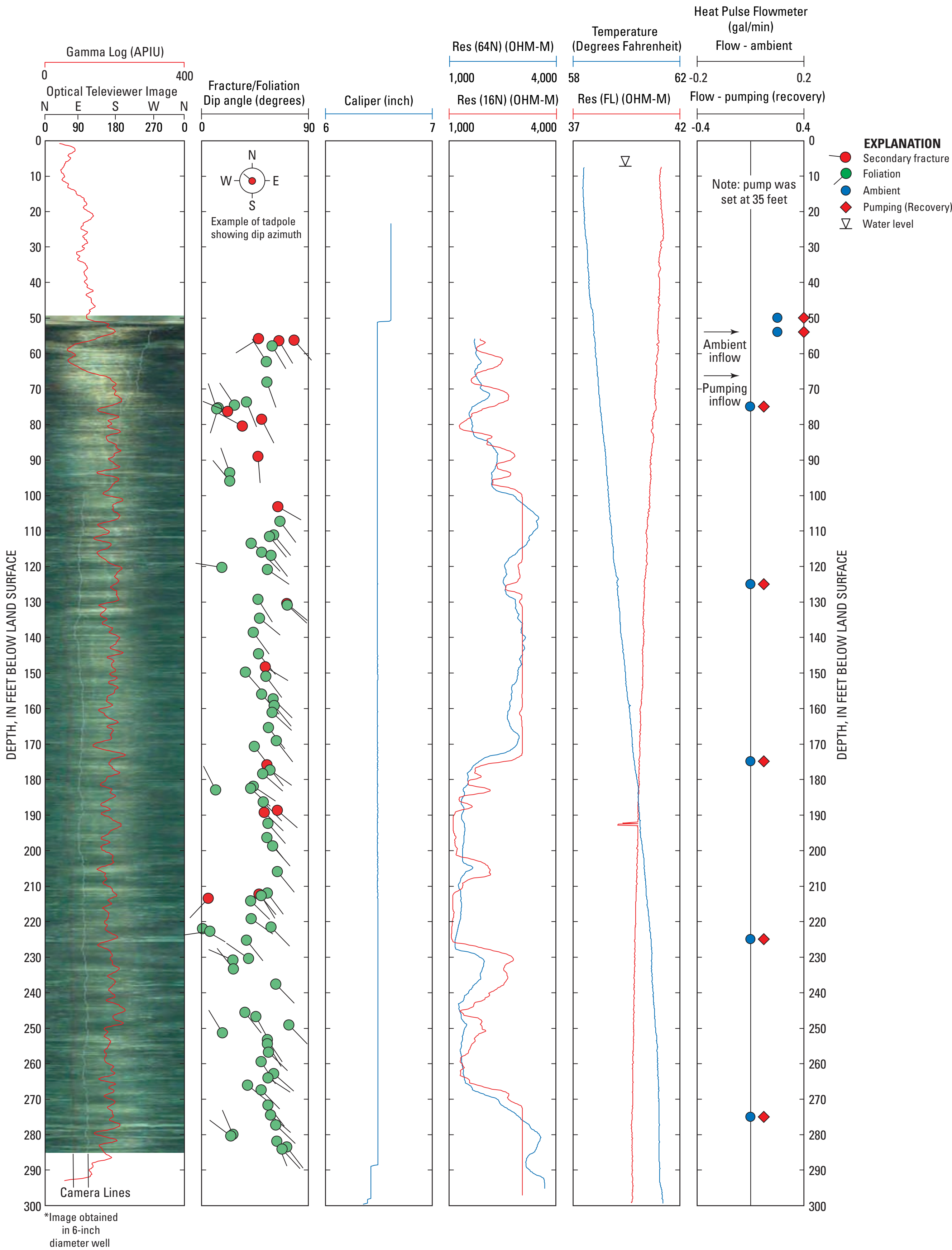

Figure 74. Geophysical logs of bedrock well MW–2D at the Bent Creek research station, North Carolina.

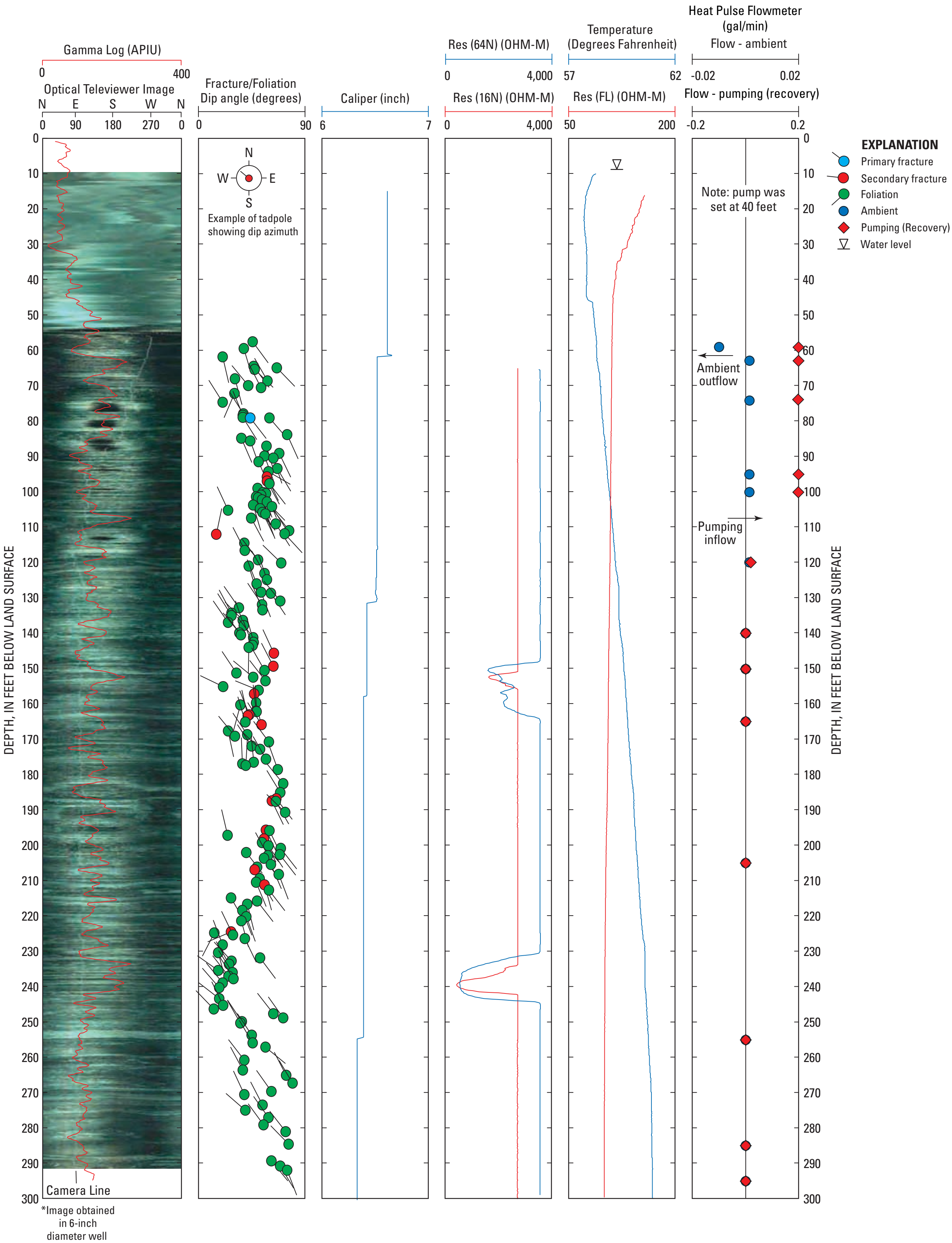

Figure 75. Geophysical logs of bedrock well MW–3D at the Bent Creek research station, North Carolina.

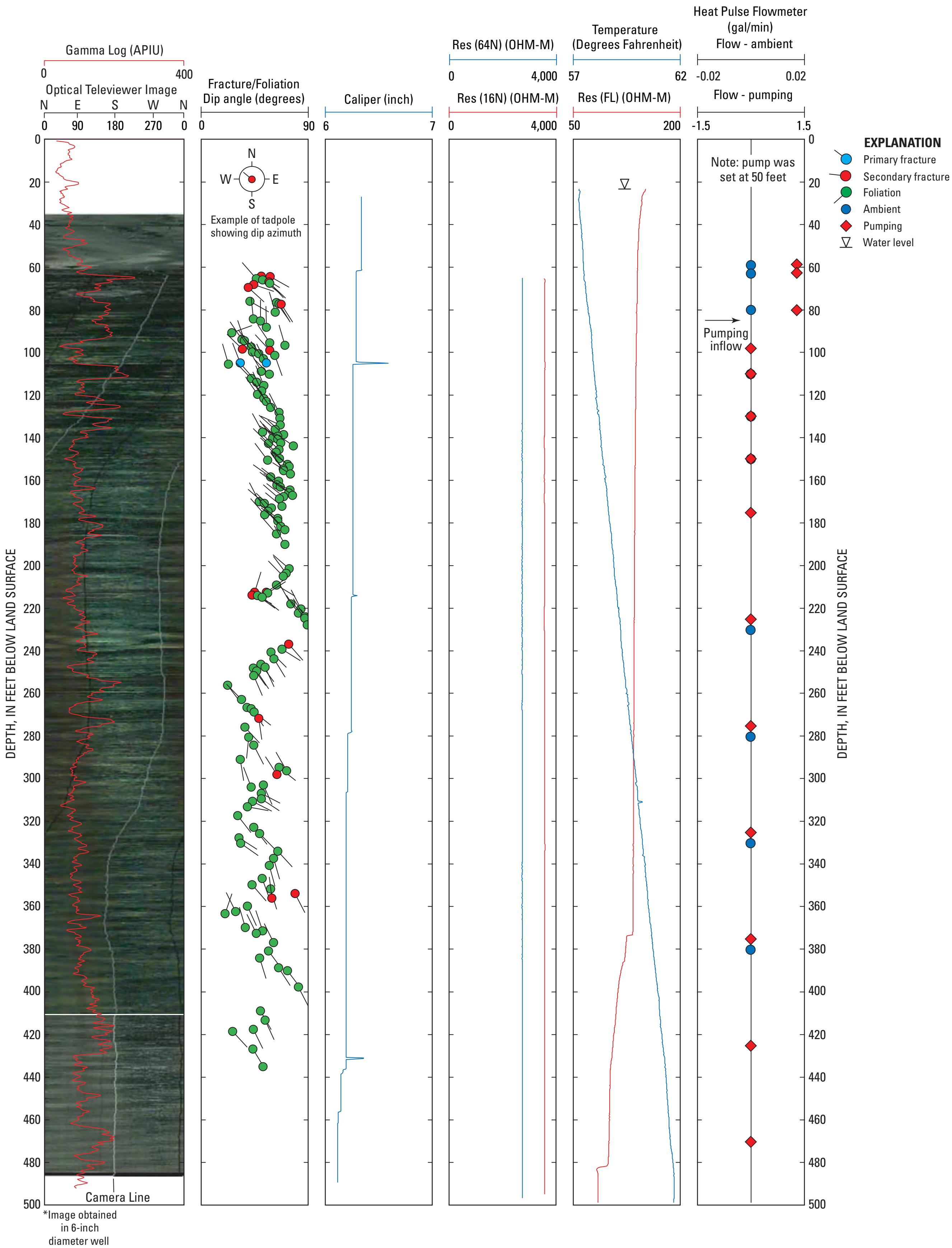

Figure 76. Geophysical logs of bedrock well MW–4D at the Bent Creek research station, North Carolina.

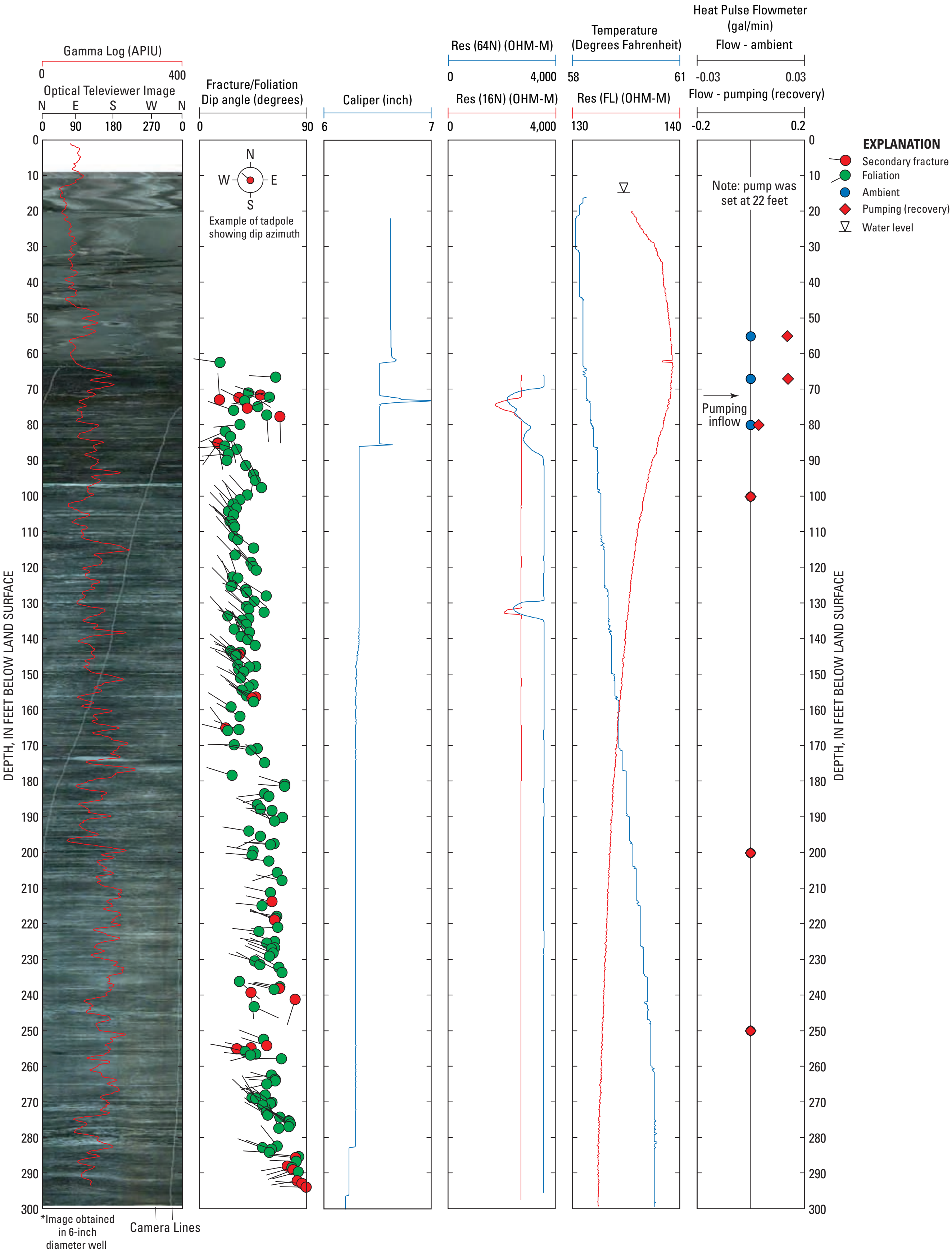

Figure 77. Geophysical logs of bedrock well MW–5D at the Bent Creek research station, North Carolina.

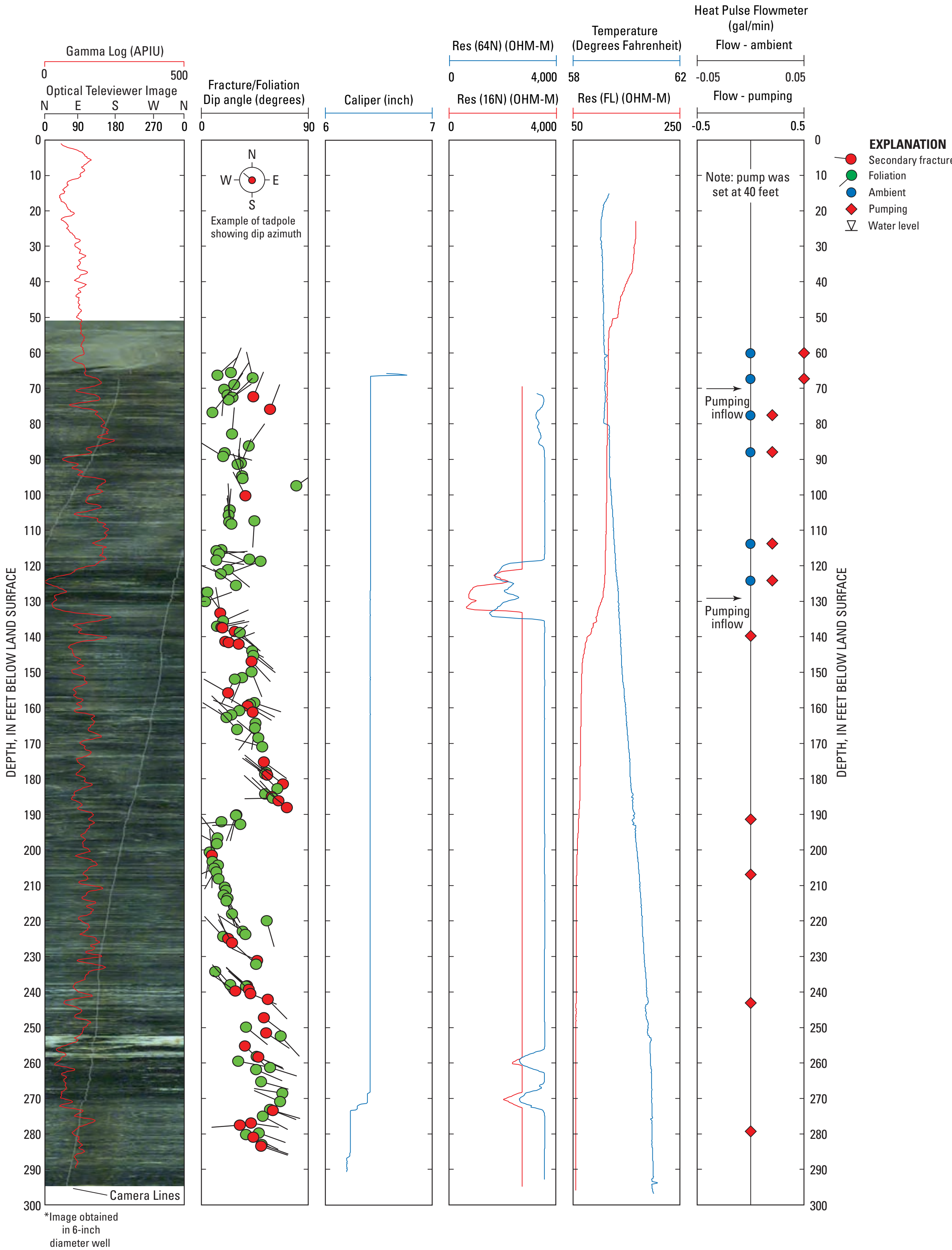

Figure 78. Geophysical logs of bedrock well MW–7D at the Bent Creek research station, North Carolina.

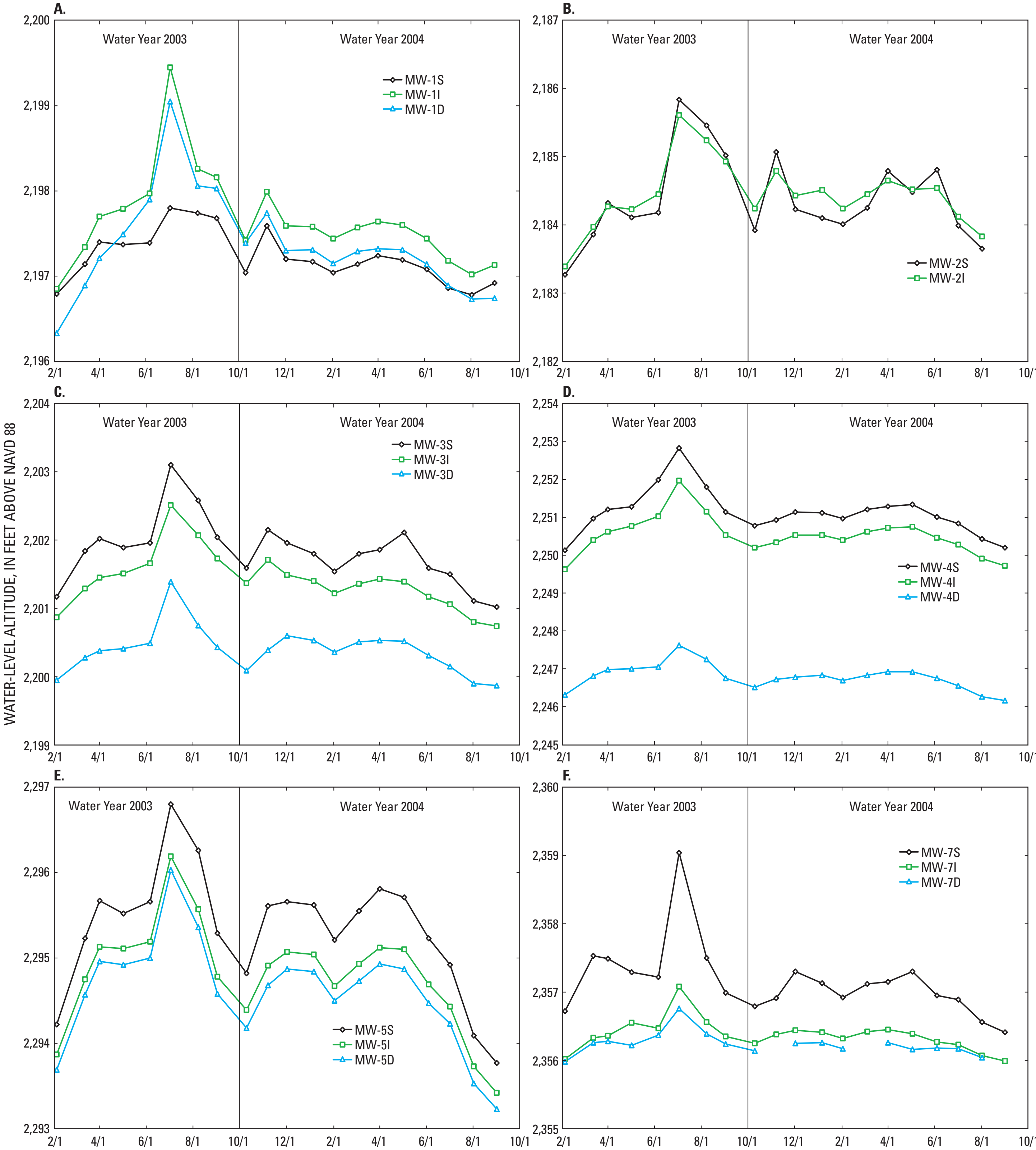

Figure 79. Periodic ground-water levels recorded in well clusters (A) MW–1, (B) MW–2, (C) MW–3, (D) MW–4, (E) MW–5, and (F) MW–7 at the Bent Creek research station, North Carolina.

cluster MW–2 ranged from about 2,183 to 2,186 ft in the shallow and transition zones. The ground-water altitude for the bedrock zone at well cluster MW–2 was higher than the casing (flowing), and water-level altitudes were not accurately measured. Ground-water altitudes at well cluster MW–3 ranged from about 2,201 to 2,203 ft in the shallow zone, from about 2,201 to 2,202.5 ft in the transition zone, and from about 2,200 to 2,201 ft in the bedrock zone. Ground-water altitudes at well cluster MW–4 ranged from about 2,250 to 2,253 ft in the shallow zone, from about 2,249.5 to 2,252 ft in the transition zone, and from about 2,246 to 2,248 ft in the bedrock zone. Ground-water altitudes at well cluster MW–5 ranged from about 2,294 to 2,297 ft in the shallow zone, from about 2,293.5 to 2,296 ft in the transition zone, and from about 2,293 to 2,296 ft in the bedrock zone. Ground-water altitudes at well cluster MW–7 ranged from about 2,356.5 to 2,359 ft in the shallow zone and from about 2,356 to 2,357 ft in the transition and bedrock zones. The water-level altitudes for the shallow zone were consistently higher than water-level altitudes in the transition and bedrock zones at well clusters MW–3, MW–4, MW–5, and MW–7. Periodic water-level data collection in the piezometers, the collection of hourly ground-water levels and water quality at cluster MW–2, and the collection of 15-minute surface-water stage and water quality at Boyd Branch did not begin until late in water year 2004 and are not included in this report. Detailed summaries of ground-water-level data recorded in the BCRS wells for water years 2003 and 2004 are published in USGS annual data reports for North Carolina (Howe and others, 2004, 2005).

Slug tests were conducted in 11 wells at the BCRS in April and September 2004. Either a 5-ft long, 3-inch diameter solid PVC slug or a 5-ft long, 4-inch solid PVC slug was used to displace water in the wells. Slug tests were conducted to estimate hydraulic conductivity in the three aquifer zones tapped by the wells—the regolith, transition zone, and bedrock. The estimates obtained are representative of conditions in the immediate vicinity of the tested wells. A summary of hydraulic conductivity values is given in table 8.

Water-quality samples were collected from all wells (excluding the piezometers) and two streams (Boyd Branch and Bent Creek) at the BCRS during April 2003. Major ion concentrations by ground-water zone are displayed in Piper (fig. 80) and Stiff diagrams (fig. 81); ranges in values of major ion concentrations and physical properties are shown in box plots (figs. 82–84).

Continuous real-time data collection began in July 2004 in all three wells in cluster MW–2 and in the nearby stream (Boyd Branch, station 0344789265), but not enough data have been collected to present in this report. Collection of continuous water-quality and water-level data in well cluster MW–2 began in August 2004. Continuous stage data in the stream have been recorded since March 2004, and water-quality data collection in the stream began in August 2004.

Table 8. Analytical results of slug tests in wells at the Bent Creek research station, North Carolina.

Well number	Screened/Open interval (feet below land surface)	Average[a] hydraulic conductivity (feet per day)
Regolith wells		
MW-1S	8–22	30
MW-2S	5–20	3
MW-3S	15–30	0.5
MW-4S	7–22	2
MW-5S	9–24	2
Transition-zone wells		
MW-1I	38–53	10
MW-2I	21–36	5
MW-3I	35–50	5
MW-5I	32–47	10
Bedrock wells		
MW-3D	61–300	0.04
MW-4D	61–501	0.2

[a]Calculated from falling-head and rising-head slug tests.

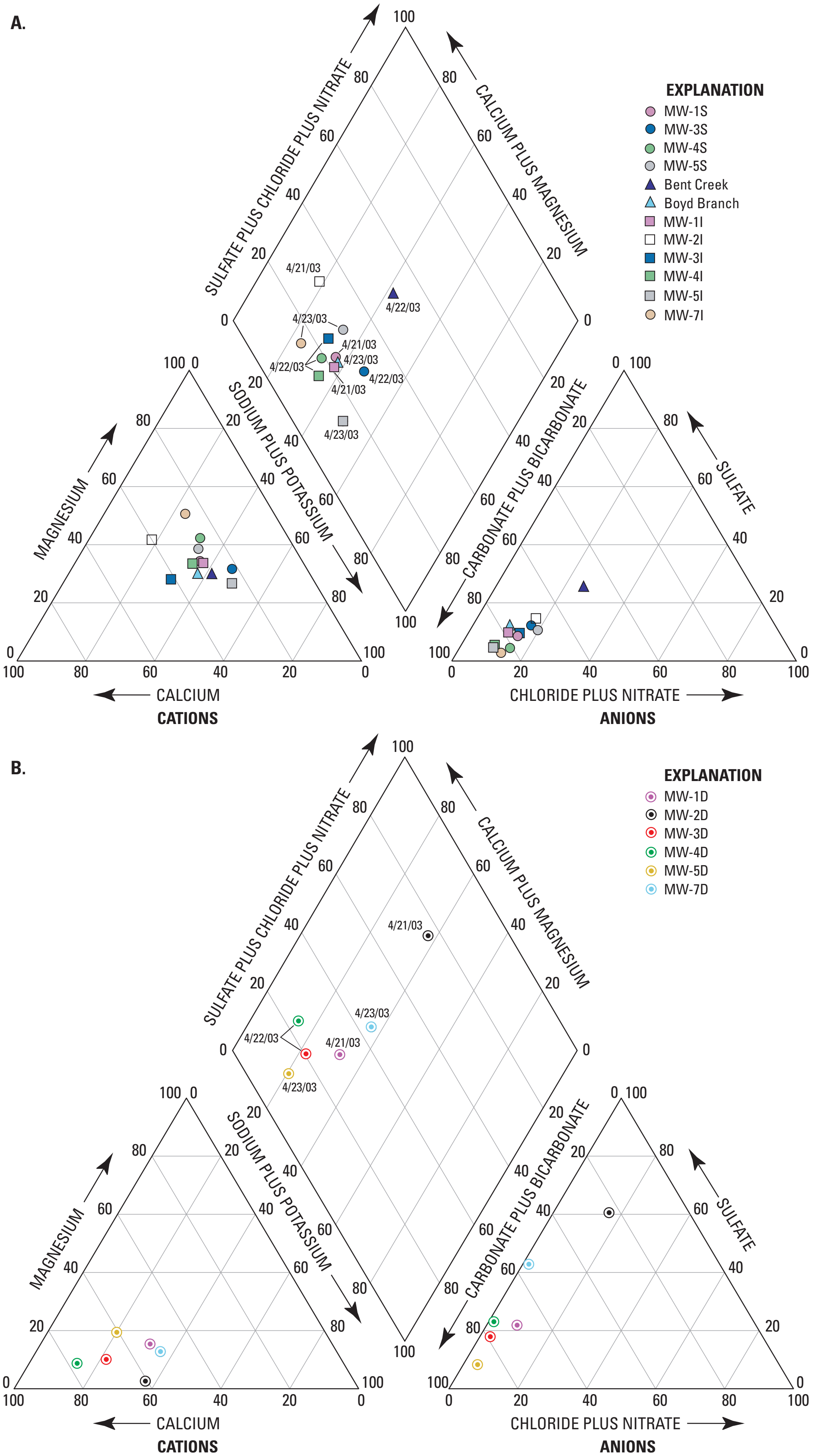

Figure 80. The water chemistry of samples from (A) regolith and transition-zone wells and surface-water sites, and (B) open-borehole bedrock wells at the Bent Creek research station, North Carolina.

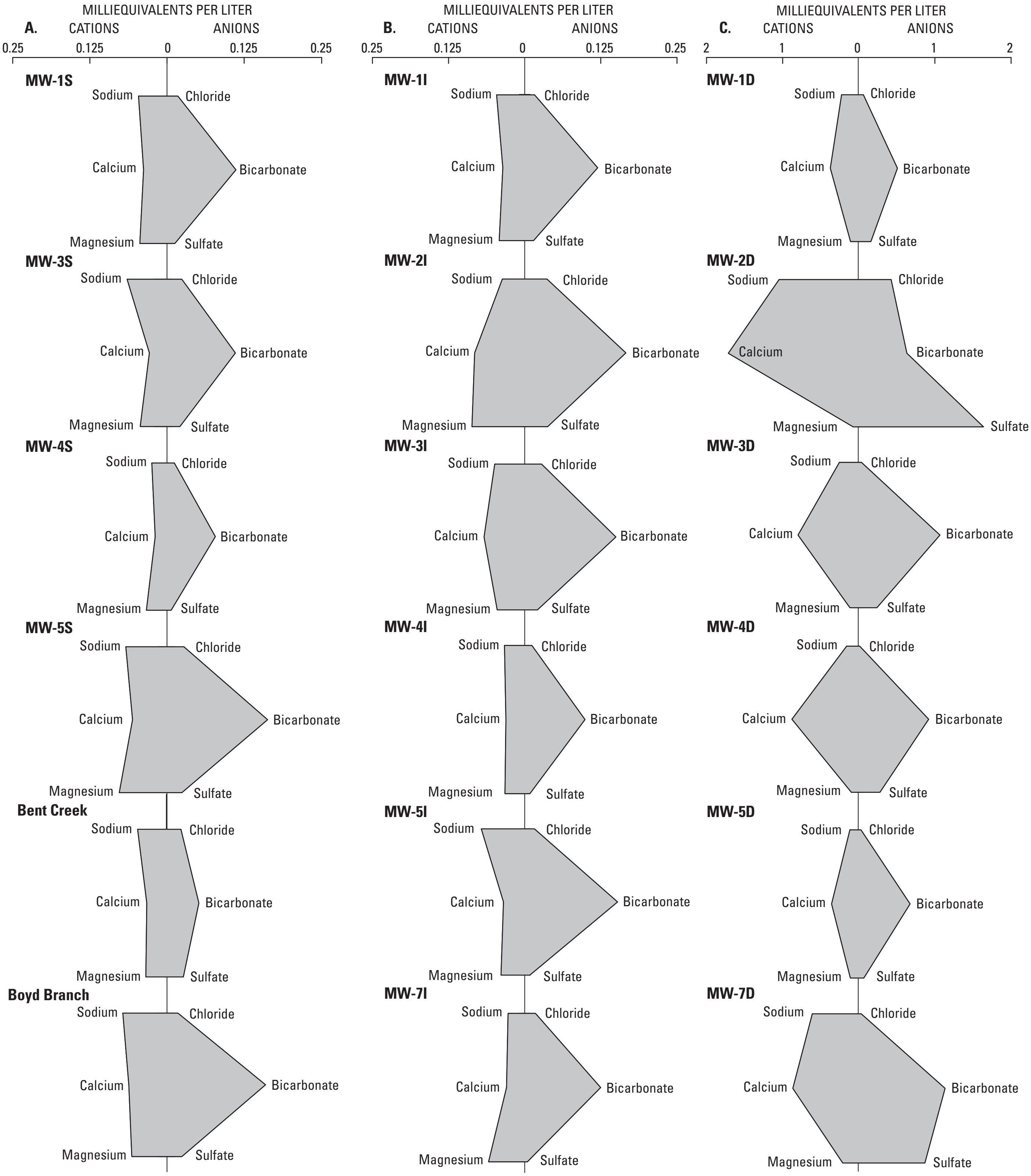

Figure 81. Major ion milliequivalents in water samples collected from (A) regolith wells and surface-water sites, (B) transition-zone wells, and (C) open-borehole bedrock wells at the Bent Creek research station, North Carolina, April 2003.

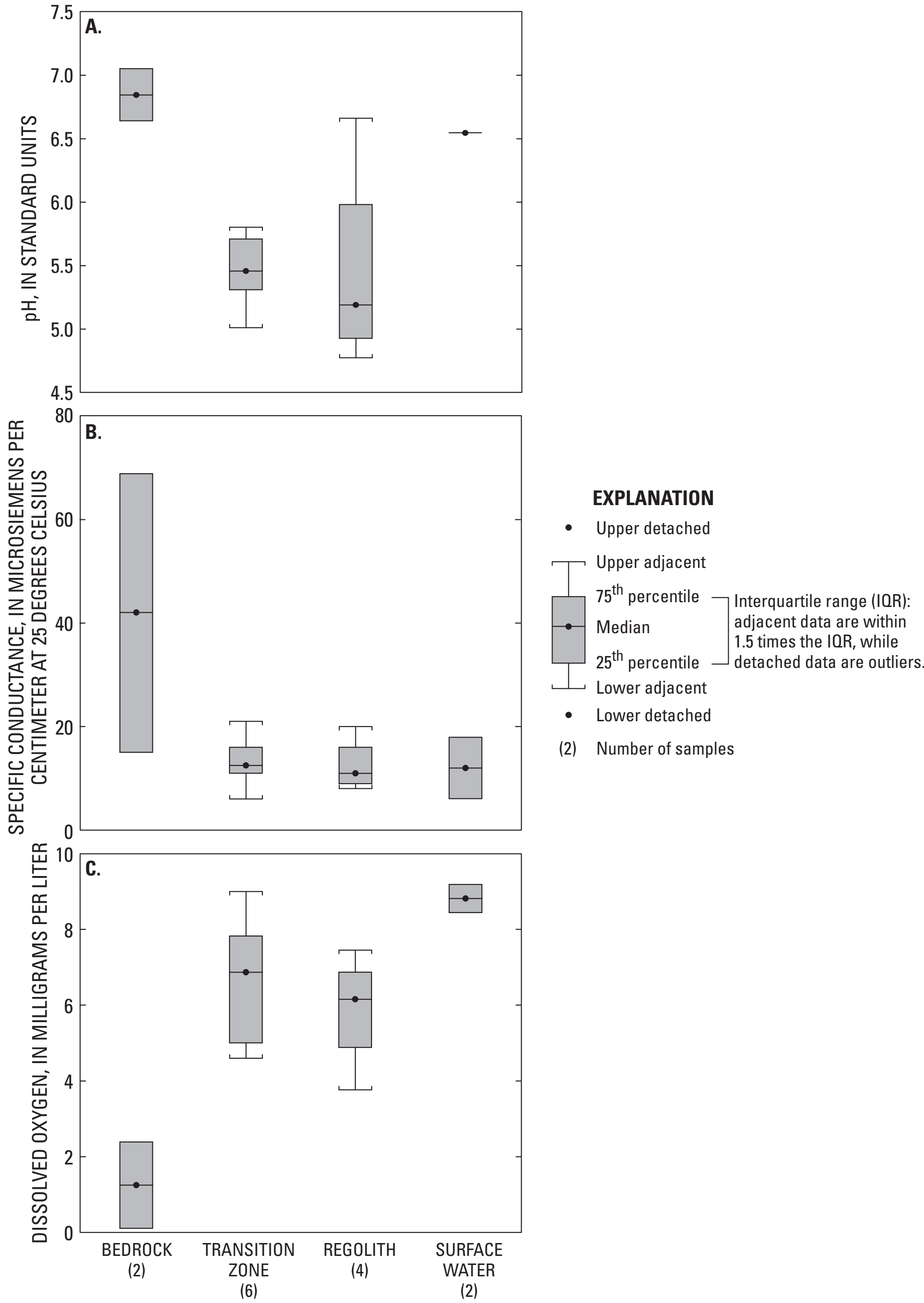

Figure 82. The range, median, and quartile statistical values for (A) pH, (B) specific conductance, and (C) dissolved oxygen for wells and surface-water sites during periodic sampling events at the Bent Creek research station, North Carolina.

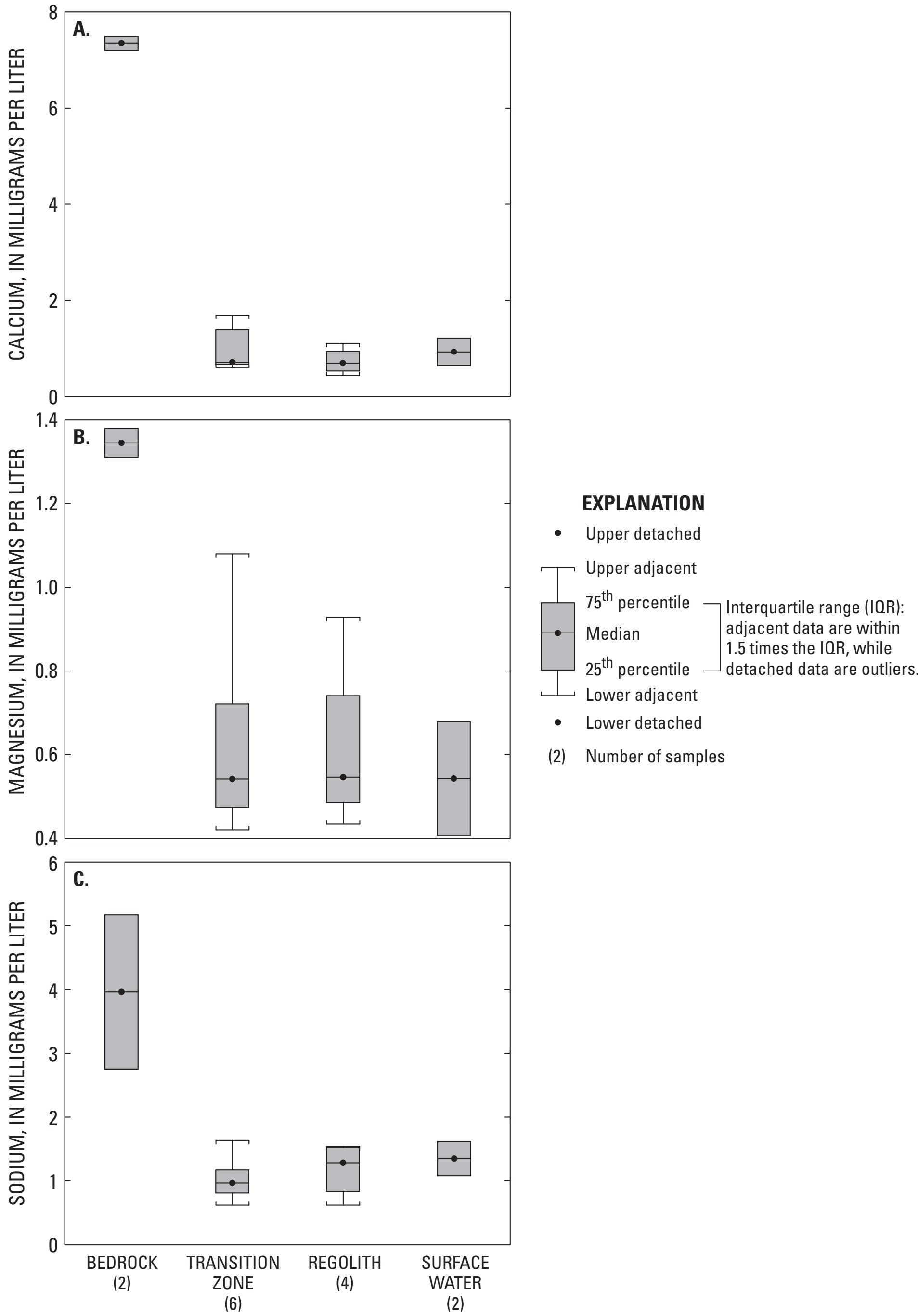

Figure 83. The range, median, and quartile statistical values for (A) calcium, (B) magnesium, and (C) sodium for wells and surface-water sites during periodic sampling events at the Bent Creek research station, North Carolina.

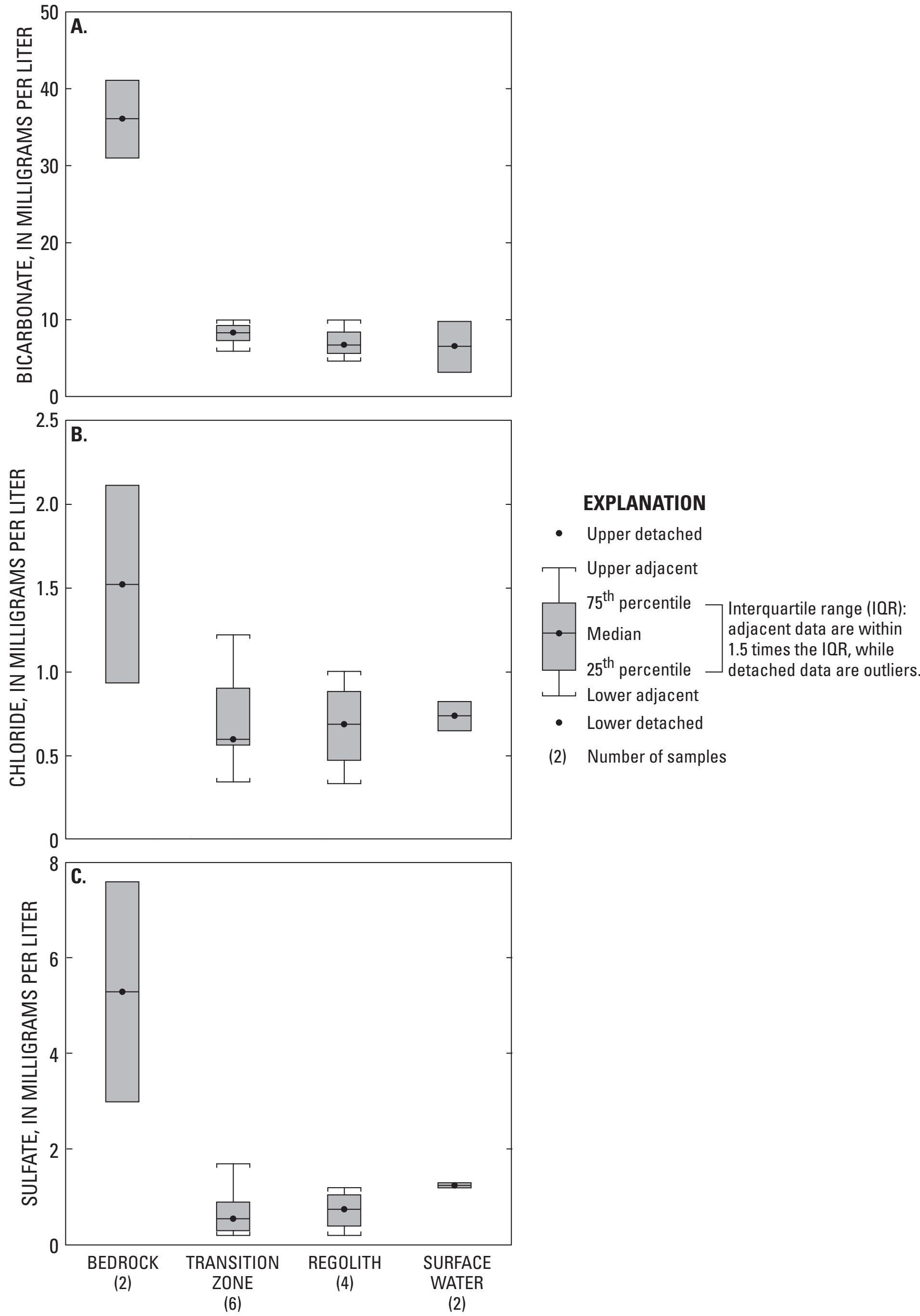

Figure 84. The range, median, and quartile statistical values for (A) bicarbonate, (B) chloride, and (C) sulfate for wells and surface-water sites during periodic sampling events at the Bent Creek research station, North Carolina.

Summary

In 1999, the U.S. Geological Survey and the North Carolina Department of Environment and Natural Resources, Division of Water Quality, began a multiyear cooperative study to measure ambient ground-water quality and characterize the ground-water-flow system in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina. To date (2006), data have been collected from 160 wells at six research stations. Data presented in this report include regional surficial geology, research-station design, well characteristics, borehole geophysical data, ground-water-quality data, and ground-water-level data from four stations (110 wells and piezometers). Data are presented for the Lake Wheeler Road research station (LWRRS, Raleigh) for the period April 2001 to September 2004, for the Langtree Peninsula research station (LPRS, Mooresville) for the period September 2000 to September 2004, for the Upper Piedmont research station (UPRS, Reidsville) for the period March 2002 to September 2004, and for the Bent Creek research station (BCRS, Asheville) for the period July 2002 to September 2004.

References

Bouwer, H. and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research v. 12, no. 3, p. 423–428.

Butler, J.J., Jr., 1998, The design, performance, and analysis of slug tests: Boca Raton, FL, Lewis Publishers, 251 p.

Chapman, M.J., Bolich, R.E., and Huffman, B.A., 2005, Hydrogeologic setting, ground-water flow, and ground-water quality at the Lake Wheeler Road research station, 2001–03, North Carolina Piedmont and Blue Ridge Mountains Resource Evaluation Program: U.S. Geological Survey Scientific Investigations Report 2005–5166, 85 p.

Daniel, C.C., III, and Dahlen, P.R., 2002, Preliminary hydrogeologic assessment and study plan for a regional ground-water resource investigation of the Blue Ridge and Piedmont Provinces of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 02–4105, 60 p.; accessed in November 2004 at *http://nc.water.usgs.gov/reports/wri024105/*

Daniel, C.C., III, and Payne, R.A., 1990, Hydrogeologic unit map of the Piedmont and Blue Ridge Provinces of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 90–4035, 1 map sheet, scale 1:500,000.

Halford, K.J., and Kuniansky, E.L., 2002, Documentation of spreadsheets for the analysis of aquifer-test and slug-test data: U.S. Geological Survey Open-File Report 02–197, 54 p.

Heller, M.J., 1996, Structure and lithostratigraphy of the Lake Wheeler area, Wake County, North Carolina: Raleigh, North Carolina State University, MS Thesis, 121 p.

Horton, J.W., Jr., and Geddes, D.J., Jr., (in press), Geologic map of the upper Wolf Island Creek watershed, Reidsville area, Rockingham County, North Carolina: U.S. Geological Survey Scientific Investigations Map 2871, scale 1:24,000, CD–ROM.

Howe, S.S., Breton, P.L., and Chapman, M.J., 2002 Water resources data, North Carolina, water year 2001, v. 2, ground-water records: U.S. Geological Survey Water-Data Report NC–01–2, 279 p.

Howe, S.S., Breton, P.L., and Chapman, M.J., 2003 Water resources data, North Carolina, water year 2002, v. 2, ground-water records: U.S. Geological Survey Water-Data Report NC–02–2, 355 p.

Howe, S.S., Breton, P.L., and Chapman, M.J., 2004 Water resources data, North Carolina, water year 2003, v. 2, ground-water records: U.S. Geological Survey Water-Data Report NC–03–2, 493 p., CD–ROM.

Howe, S.S., Breton, P.L., and Chapman, M.J., 2005 Water resources data, North Carolina, water year 2004, v. 2, ground-water records: U.S. Geological Survey Water-Data Report NC–04–2, 389 p.; available online at *http://pubs.water.usgs.gov/wdrnc04/*

LeGrand, H.E., and Nelson, P.F., 2004, A master conceptual model for hydrogeological site characterization in the Piedmont and Mountain region of North Carolina, A guidance manual: Raleigh, North Carolina Department of Environment and Natural Resources, Division of Water Quality, Groundwater Section, 50 p.

Merschat, C.E., and Carter, M.W., 2002, Bedrock geologic map of the Bent Creek Research and Demonstration Forest, Southern Research Station, USDA Forest Service, including the North Carolina Arboretum and a portion of the Blue Ridge Parkway: Raleigh, North Carolina Geological Survey, Geological Survey Map Series 9, scale 1:12,000.

North Carolina Department of Environment and Natural Resources, Division of Water Quality, Aquifer Protection Section, 2002, Standard operating procedures for ground water research stations, Resource Evaluation Program, Piedmont and Mountains of North Carolina: available online at *http://mro.enr.state.nc.us/gw/repweb/Index_REP.html*

North Carolina Geological Survey, 1985, Geologic map of North Carolina: Raleigh, North Carolina Geological Survey, 1 sheet, scale 1:500,000.

Parker, J.M., III, 1979, Geology and mineral resources of Wake County: Raleigh, North Carolina Department of Natural Resources and Community Development, Bulletin 86, 123 p.

Piper, A.M., 1953, A graphic procedure in the geochemical interpretation of water analyses: Washington, D.C., U.S. Geological Survey, Ground-Water Chemistry Notes, no. 12, 14 p.

Shapiro, A.M., 2001, Characterizing ground-water chemistry and hydraulic properties of fracture-rock aquifers using the Multifunction Bedrock-Aquifer Transportable Testing Tool (BAT3): U.S. Geological Survey Fact Sheet FS–075–01, 4 p.

Sincich, T., 1993, Statistics by example: New Jersey, Prentice Hall, Inc., p. 136–140.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, p. 15–17.

U.S. Geological Survey, 1974, Surface water supply of the United States, 1966–70, part 2. South Atlantic Slope and Eastern Gulf of Mexico Basins, v. 1, Basins from James River to Savannah River: U.S. Geological Survey Water-Supply Paper 2104, p. 3–10.

U.S. Geological Survey, 1975, Quality of surface water of the United States, 1970, part 3. Ohio River Basin: U.S. Geological Survey Water-Supply Paper 2153, p. 1–2.

U.S. Geological Survey, 2005a, North Carolina water-use data tables, 2000: accessed in January 2005 at *http://nc.water.usgs.gov/wateruse/data/Data_Tables_2000.html*

U.S. Geological Survey, 2005b, Vertical flowmeter logging: accessed in January 2005 at *http://water.usgs.gov/ogw/bgas/flowmeter/*

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, available online at *http://pubs.water.usgs.gov/tm1d3/*

Weaver, J.C., 2005, The drought of 1998–2002 in North Carolina—Precipitation and hydrologic conditions: U.S. Geological Survey Scientific Investigations Report 2005–5053, 88 p.

Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T., 1999, National field manual for the collection of water-quality data—Collection of water samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4 [variously paged].

Prepared by:

U.S. Geological Survey
Enterprise Publishing Network
North Carolina Water Science Center
3916 Sunset Ridge Road
Raleigh, NC 27607

USGS

Huffman and Others—**Compilation of Water-Resources Data and Hydrogeologic Setting in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina, 2000–2004**

USGS SIR 2006–1168

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